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THE INSTITUTE OF PETROLEUM AND THE INSTITUTION OF FIRE ENGINEERS.

A joint meeting of the Institute of Petroleum and the Institution of Fire Engineers was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, September 14, 1949.

E. A. Evans, M.I.Mech.E., F.R.I.C. (President of the Institute of Petroleum) presided during the early part of the proceedings, and A. H. Nisbet, M.B.E., G.M. (President of the Institution of Fire Engineers) occupied the Chair during the reading and discussion of the papers.

The Minutes of the preceding Ordinary General Meeting of the Institute of Petroleum, held on May 11, 1949, were read, confirmed, and signed.

The President of the Institute, opening the technical proceedings, said:

Professor J. S. S. Brame took as his subject "Fire Hazards and Fire Extinction" for his Presidential Address in 1923. He suggested that a most instructive evening could be spent in discussing this subject. As it has taken twenty-six years to arrange this meeting this evening it ought to be good. For many years some of us have believed that a red-hot coal or a bright end of a vigorously smoked cigarette will not ignite petrol, whereas an electric spark will. It has annoyed us, therefore, when we have been forbidden to smoke in an oil refinery. Perhaps this evening we shall be disillusioned.

Years ago I was told that an explosion was caused in the United States when a tom cat, after a violent struggle, parted with its static charge on entering a lethal chamber containing petroleum gas.

Whether all forms of electric discharge will ignite petroleum I do not know, but in my youth Sir Oliver Lodge stated that an ordinary parrot cage forms a practically perfect protector against lightning. He did not say whether it should contain a talking parrot to tell the lightning where to go if it wanted a fire.

Fire-fighting is a specialized subject, with long-established practice, though the science of fire-fighting is, perhaps, more recent, and was given fresh impetus during the recent hostilities.

The Department of Scientific and Industrial Research combines with the Fire Offices Committee to run the fire-research organization, for which body the group of workers presenting papers to-night conduct their experiments. The work described was carried out, partly at Llandarcy and partly at the Imperial College of Science and Technology, Kensington.

The Institution of Fire Engineers takes care of the scientific aspects of fire engineering in general, and joins with us to-night to hear these papers.

The Institute of Petroleum has a special interest in fighting oil fires, and its members probably get more practice even than regular firemen in this branch of fire-fighting.

Dr J. H. Burgoyne of the Chemical Engineering and Applied Chemistry Department of the Imperial College of Science and Technology leads a group of workers, of whom Messrs Katan and Richardson are two.

This group carried out extensive work on the study of fires in open tanks containing petroleum products, and, at a joint meeting of our two Institutions, presented papers on their work in December 1946. The *Journal* in which these papers were published was very quickly sold out, indicating quite a large measure of interest in this subject. To-night's papers report further work along the lines then started.

Mr Thornton, who is well known to many of you, is a Fellow of our own Institute, and a Licentiate of the Institution of Fire Engineers, being, in fact, their honorary consultant on oil fires. He was a member of the " F " Committee of the Department of Scientific and Industrial Research during the war, and collaborated with Dr Burgoyne's group in much of the work then carried out. He is in charge of the fire protection of the Llandarcy refineries and properties, and his paper is intended to form the basis of discussion in an attempt to assess the practical significance of the small scale results, and it is hoped will provoke a lively discussion.

For the discussion it will be my pleasure to ask the President of the Institution of Fire Engineers, A. H. Nisbet, who is the Fire-master of the Lanarkshire Authority in Scotland, to preside.

My pleasant duty is now to offer a very cordial welcome to the President and members of the Institution of Fire Engineers, and to thank them for co-operating with the Institute of Petroleum in this important subject.

We are also honoured by the presence of Viscount Falmouth, under whom, and with whose inspiration, Dr Burgoyne and his colleagues have worked. It would be fitting if we asked Viscount Falmouth to address a few words to us, for he is a busy man and may have to leave early.

THE RT. HON. VISCOUNT FALMOUTH : I would like to say how very much indebted we are to Messrs Burgoyne, Katan, Richardson, and Thornton for the papers they have put forward.

The first three gentlemen were members of the Fire Research Division, established during the war; this question of burning liquids was indeed a very burning question then. These three gentlemen were the " back-room boys " who had to tackle the very difficult problems involved, and we are very much indebted to them indeed for all they did to help the country during a very difficult period.

Mr Thornton was our very good friend at Llandarcy, and helped us in every conceivable way; I am certain that often the Fire Research Division must have been an infernal nuisance, but he always came up smiling and did everything he could to enable Dr Burgoyne and his colleagues to carry out their experiments.

Since those early days a great deal has been done, and a great deal of what was not very obvious then has been explained and further developed. In the papers before us there are very many matters of practical interest to us all, particularly, I think, the discussion on base injection and top pouring. I am glad that Dr Burgoyne has been able to find time to clear up some of the outstanding problems.

The following paper was presented :

THE APPLICATION OF AIR-FOAM TO OILS BURNING IN BULK.

By J. H. BURGOYNE,* L. L. KATAN,* and J. F. RICHARDSON.*

SUMMARY.

Part I. The way in which the application of air-foam extinguishes burning oils has been studied. The mechanism is found to depend on the burning characteristics of the oil and on whether the foam is applied from above the burning surface or by base injection. With an adequate rate of top application to an oil having a surface temperature during burning of not more than 100° C (benzole, motor spirit), a blanket of foam can form at once and appears to extinguish the fire chiefly by interrupting the transfer of heat from the flames to the oil surface and hence preventing volatilization of the fuel. If the surface temperature is above 100° C it must be reduced to this figure (accompanied by foam breakdown) before a blanket can form. In some instances (heavy lubricating oil) the fire is extinguished before this latter condition is achieved, but in others (gas oil) the surface temperature necessary for extinction is below 100° C, and a blanket must be formed before extinction occurs. With oils that form a high-temperature hot-zone during burning, the hot-zone must be cooled to a certain temperature (about 130° C in the case of Pool fuel oil) before the flames subside. This cooling by the foam results in vigorous frothing, but there is no question of blanket formation. When the foam is applied to Pool fuel oil by base injection, the cooling of the hot zone is augmented by a stirring effect which mixes underlying cold oil with the hot. If the application is slow, extinction occurs at a hot-zone temperature of 130° C, but if rapid, at lower temperatures, when, however, (it is supposed) the surface temperature has just reached 130° C. These effects are thought to be associated with the "temporary" and "permanent" extinguishing effects noticed with this type of oil in previous air-stirring experiments.

Part II. The extinction of burning Pool fuel oil with top- and base-applied air-foam has been studied quantitatively on a 40-gal scale. The numerical results are, of course, peculiar to the conditions of experiment, but the following general conclusions are indicated.

(i) To achieve extinction in any length of time, foam from overhead must be applied above the minimum rate necessary to absorb the normal heat input from the flames to the hot zone. Above this rate, the time for extinction is related directly to the amount of hot zone that has to be cooled (*i.e.*, time of previous burning) and inversely to the rate of foam application.

(ii) The extent to which frothing occurs is related directly to the amount of hot zone present (*i.e.*, time of burning) and to the rate of application of foam from overhead, although the extent of frothing tends to a limiting value at high application rates for a given depth of hot zone.

(iii) With base application, the minimum foam rate necessary for extinction is lessened on account of stirring, which causes cold oil to mix with the hot zone and assist in cooling it. Above the minimum rate the relationship between extinction time and foam rate appears to be discontinuous at moderate rates, owing, it is thought, to the "temporary" and "permanent" extinguishing effects of stirring, to which attention was drawn in Part I. At low rates of application there is little difference in the frothing effects due to top and base application, but at high rates the latter causes much the more extensive frothing.

* Department of Chemical Engineering and Applied Chemistry, Imperial College, London.

PART I. GENERAL EFFECTS WITH REPRESENTATIVE GRADES.

By J. H. BURGOYNE and L. L. KATAN.

INTRODUCTION.

IN a previous paper [1] the mechanism of bulk burning of representative petroleum oils was discussed, and, on a basis of burning behaviour, a broad classification of grades was suggested into : (1) those that form a hot zone beneath the surface during burning (crudes, fuel oils, and motor spirit), and (2) those that do not (refined oils other than motor spirit). It was further shown that there is an important distinction in practice between motor spirit, whose hot-zone temperature was found to be below 100° C, and the other hot-zone forming oils, for which the temperature was considerably above this figure. In particular, the latter oils are subject to frothing and slopover on the addition of water during burning, whereas motor spirit is not. With those grades that do not form a hot zone, the question of frothing and allied effects does not arise, except possibly with those of high surface temperature.

These effects of water are of great practical interest, for this medium, particularly in the form of foam, is the one most used at the present time for combating large oil fires. Reference to the scientific and technical literature shows, however, that, although the properties of foam itself have been studied closely [2] and some measurements made on the quantitative aspect of its use in extinguishing certain types of oil fire,[3] the mechanism by which it effects fire extinction and the associated effects, such as frothing, have not received much attention.

The work described in the present paper was undertaken in an attempt to fill this gap. First of all, using some representative grades of oil, the effects of foam application on normal burning behaviour were studied, using the technique described previously.[1] Part I describes and considers the results obtained.

EXPERIMENTAL.

Apparatus.

The tank used was that previously employed for small-scale experiments.[1] It was about 40 in deep and 22 in diameter, and thus had a full capacity of 55 gal. Oil temperatures at specified levels were registered by means of horizontal iron–constantan thermocouples projecting through glands in the side of the tank, and the change of weight of the oil contents could be followed by means of a hydrostatic pressure gauge communicating with the tank bottom. The tank was lagged with asbestos to an average thickness of 3 in.

Foam of predetermined characteristics was supplied to the tank from a generator operated by compressed air at a regulated pressure of 35 p.s.i. and was applied either from the open end of a 1-in gas pipe laid over the rim of the tank (" top application ") or through a $\frac{3}{4}$-in gas pipe welded into the base (" base application "). In the latter case the foam line incor-

porated an inverted U-tube which prevented the flow of oil back into the foam generator.

The foam was produced from a 3 per cent solution of pyrene compound. Its characteristics were checked before and after every experiment by sampling from the supply pipe and measuring the expansion (*i.e.*, the ratio : weight of a given volume of water ÷ weight of the same volume of foam). The flow rate was checked by measuring the time of delivery of a standard volume from the supply pipe.

Grades of oil used.

Experiments were carried out with five grades of oil having widely differing burning behaviours. Their physical properties are given in Table I. The oils and their particular characteristics are listed below :—

(1) Pure benzole. A technically pure fraction having a narrow boiling range. It does not form a hot zone and has a surface temperature during burning (viz., the final boiling point) *below* the boiling point of water.

(2) Pool gas oil. Does not form a hot zone, but has a surface temperature during burning *above* the boiling point of water (about 360° C).

(3) Pool lubricating oil grade 20. An extremely viscous oil. It does not form a hot zone during burning, but the surface temperature is very high (about 580° C).

(4) Pool motor spirit. This forms an accumulating hot zone of uniform temperature. The temperature of the hot zone was just below the boiling point of water under the conditions of experiment, but it is thought that the hot-zone temperature for motor spirits could exceed 100° C in some circumstances.

(5) Pool fuel oil. This forms a hot zone whose temperature considerably exceeds the boiling point of water.

The effects of the top application of foam to all of these oils during burning were studied. With Pool fuel oil, base-application experiments were also carried out.

TABLE I.

Physical Properties of Oils Used.

Grade.	Sp. gr. at 60° F.	V.R.I. Sec at 100° F.	Water content, %.	Distillation (A.S.T.M., ° C).		
				I.B.P.	50%.	F.B.P.
Pure benzole .	0·883	—	—	77	79·5	93
Pool gas oil .	0·850	—	—	185	277·5	352
Pool lub. oil, grade 20 .	0·940	5416	—	— [1]	—	—
Pool motor spirit	0·738	—	—	48	101	189
Pool fuel oil .	0·921–0·934	198–213	0·35–0·6	— [2]	—	—

[1] Specified boiling range approximately 500–600° C.
[2] One sample of Pool fuel oil gave I.B.P. 190°, 50% 380° C.

Results.

Pure benzole.

The application of foam was begun after 27¾ min burning, the rate of application * being 1·65 g.p.m. at an expansion of 10·7 (1·5 lb/min of water): the foam had a high dispersion (*i.e.*, was rather stiff). The fire was completely extinguished in 13 min. During the process of extinction the foam formed a discrete layer which accumulated continuously though not uniformly over the oil surface. The surface temperature showed a slight downward trend during the application of foam from the normal figure of about 91° C to 65° to 70° C at the moment of extinction. The topmost layers of the foam seemed to approach the temperature of boiling water while substantial flaming continued, and the middle layers had temperatures intermediate between this and the benzole surface temperature. When extinction was nearly complete, however, the upper part of the foam became colder than that in contact with the benzole surface.

Pool gas oil.

The application of foam was begun after the oil had burned for 58½ min. The process of extinction occupied 21 min, and during this time the initial foam application rate of 0·57 g.p.m. (expansion = 9·3; rate of application of water = 0·6 lb/min), which appeared insufficient to control the fire, was increased on three separate occasions, the final rate being 1·79 g.p.m. (expansion = 14·1; rate of application of water = 1·3 lb/min).

The temperature readings taken during this experiment showed that in the earlier stages of foam application, such foam as built up on the oil surface assumed the temperature of boiling water. Direct observation, in fact, revealed that at this time a thin layer of oily froth was being formed due to contact between the foam and the oil, the surface temperature of which was initially about 360° C. It was only when the rate of application of foam was such that white foam began to accumulate on the surface that the fire came under control. At this stage the foam and surface-oil temperatures dropped somewhat below 100° C.

During the application of foam, the underlying oil gradually warmed up. This feature had not been observed with benzole, and it may be attributed to the falling through the oil of drops of hot water resulting from the breakdown of foam at the surface. After the experiment, some 2 gal of water were drained from the base of the tank.

Pool lubricating oil, grade 20.

The oil was allowed to burn for 66 min before the application of foam was begun. The application rate was between 1·83 g.p.m. (expansion = 11·0; rate of application of water = 1·7 lb/min) and 2·06 g.p.m. (expansion 9·8; water, 2·1 lb/min), and this was sufficient to extinguish the fire in 1¾ min, although the tank walls were so hot that the application was continued for some time to avoid possible re-ignition.

By direct observation it was seen that foam began to break down in

* In all cases, total rates of application of foam or water are quoted; *i.e.*, over the whole area of the burning surface (2·6 sq. ft.).

contact with the hot oil surface, forming a dark froth as with gas oil. In the present experiment, however, this breakdown of foam continued after the fire had gone out, and, in fact, a further 3 min elapsed before the building up of white foam commenced. From this it may be presumed that at the time of extinction the surface temperature was still above 100° C. This was borne out by the temperature measurements, which also showed that 1 in below the surface the oil temperature did not begin to fall until 2½ min after extinction.

One object of experimenting with this oil was to see if any great amount of frothing would result from application of foam to an oil which does not form a hot zone, but nevertheless has a surface layer of considerable heat content. In fact, the depth of frothing was very small and not of practical importance.

No water could be drained from the tank after this experiment. This is not surprising in view of the short time of application of foam, the high temperature near the surface (which would tend to increase the proportion of water evaporated), and the high oil viscosity.

Pool motor spirit.

In a preliminary experiment with motor spirit that had burned for 30 min, it was found that a rate of application of foam of about 1·75 g.p.m. (expansion = 10·4) was just sufficient to extinguish the fire. This rate (actually 1·70 g.p.m., expansion 11·3, to 1·74 g.p.m., expansion 10·7) was used in a second experiment after 44 min burning, and careful observations of temperature were made. Extinction was complete in 14 min.

The full results are shown in Fig. 1. The upper part of the diagram illustrates temperature changes at fixed levels in the tank, and the lower diagram shows the change of pressure at the bottom of the tank due to loss of spirit by burning. Both are plotted on the same time base. In the temperature diagram, height above the tank bottom is marked on the left-hand ordinate, on which the positions of thermocouples are indicated. The axis of each thermocouple is employed as the time ordinate for corresponding temperature records plotted according to scales shown on the right-hand side.

In these experiments, foam began to build up on the liquid surface from the first application. This is consistent with the view that the surface temperature in this grade does not much exceed the hot-zone temperature, which is shown in Fig. 1 to be 94° C. Nevertheless, as can be seen from the figure, the hot zone cooled during the addition of foam, and at the time of extinction had reached 38° C. The underlying liquid meanwhile became warmed up, as though by the falling of hot water drops and interdiffusion of hot and cold zones. After the experiment, about 2¼ gal of water were withdrawn from the base of the tank, as compared with not more than 2½ gal actually applied. This clearly shows that although foam broke down in contact with the spirit, there was little volatilization of water. A repetition of the experiment with the thermocouples in different positions relative to the surface confirmed the results already obtained.

It does not seem likely that cooling of the hot zone is itself the material factor in causing extinction with this grade. As will be seen from Fig. 1, the hot-zone temperature reached a stationary value some time before the

fire actually went out. During this later phase, most of the surface was covered with foam, but the fire continued to burn in a small way, fed by vapour through cracks between old and new foam and adjacent to the wall. Complete extinction appeared to depend on completely covering the surface with foam.

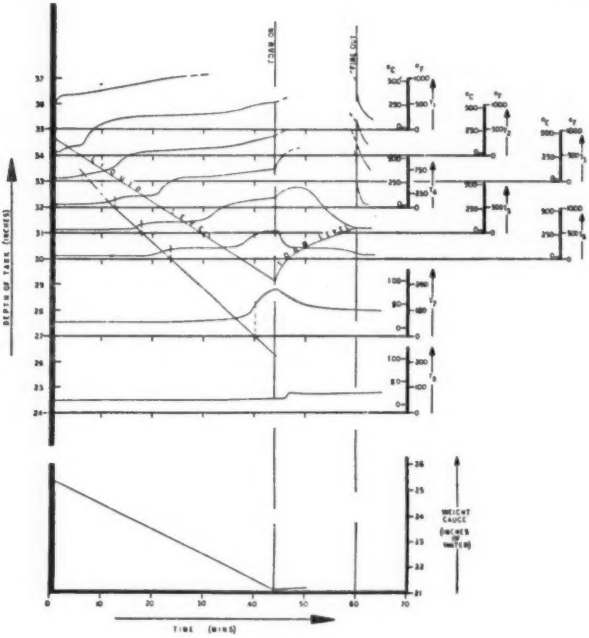

FIG. 1.

TEMPERATURE CHANGES DURING THE TOP APPLICATION OF FOAM TO BURNING POOL MOTOR SPIRIT.

Pool fuel oil.

The results of an experiment with fuel oil are shown in Fig. 2. The period of pre-burning was 33 min and the rate of application of foam 0·92 g.p.m. (expansion 10·7 to 11·3) : extinction was effected in 13 min. During the period of extinction a number of well-defined characteristics were shown in this and in another similar experiment. They may be summarized as follows.

Foam interacted with the hot-zone oil causing a copious formation of froth at a fairly steady rate. As the volume of the froth increased its temperature decreased, but at any instant the temperature was nearly uniform throughout the froth layer. When the temperature reached 130° C the fire went out.

The normal formation of the hot zone was arrested during extinction and the temperature of the underlying cold oil was not changed. No water

could be withdrawn from the base of the tank at the end of the experiment. From this it appears that, although the foam was fully broken down by the hot-zone oil, no liquid water escaped into the cold oil below. In view of the temperature and depth of the hot zone throughout the period of foam application, this result is not altogether surprising.

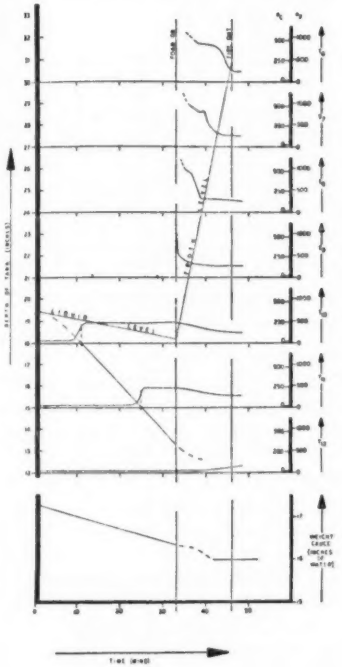

FIG. 2.

TEMPERATURE CHANGES DURING THE TOP APPLICATION OF FOAM TO BURNING POOL FUEL OIL.

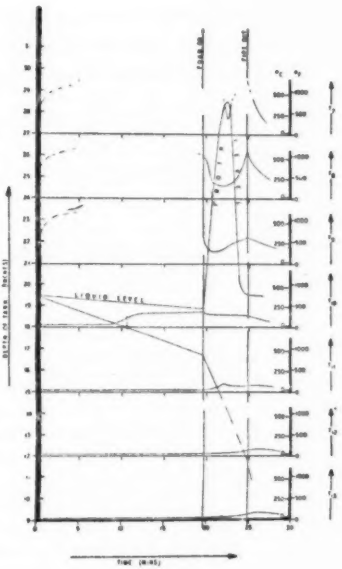

FIG. 3.

TEMPERATURE CHANGES DURING THE LOW-RATE BASE APPLICATION OF FOAM TO BURNING POOL FUEL OIL.

It is important to note that the height of the froth layer reached its greatest value just at the time of extinction. Use was made of this observation in measurements of the dependence of the amount of frothing on other variables which are described in the second part of this communication.

Base injection of foam : Pool fuel oil.

Results with the base injection of foam varied according to whether the rate of foam injection was low or high, and a typical experiment of each kind will be described.

Low rate. The full results are shown in Fig. 3. The rate of foam application varied rather widely during the experiment, commencing at 1·07 g.p.m. (expansion = 13·5) and falling to 0·69 g.p.m. (expansion = 12·6)

as measured from a free outlet in the supply line. The period of pre-burning was 19¼ min, and extinction was complete in 5½ min.

As might be anticipated, the hot zone was extended and cooled by intermixture with the cold oil below, just as during air-stirring. Contact of foam with the hot zone, however, caused cooling of the latter and copious

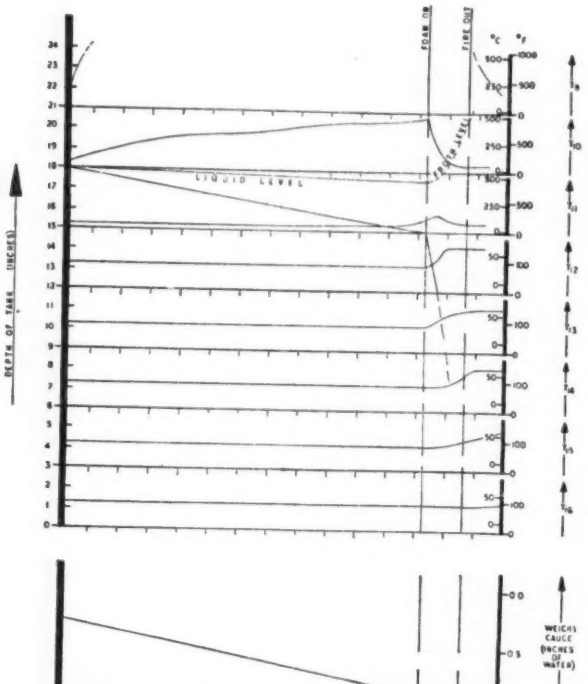

FIG. 4.

TEMPERATURE CHANGES DURING THE HIGH-RATE BASE APPLICATION OF FOAM TO BURNING POOL FUEL OIL.

frothing. Temperatures were less uniform than with top application, but it is clear that extinction again occurred at a " hot-zone " (froth) temperature of about 130° C.

The froth level in this case did not rise continuously throughout the period of extinction, but rose to a maximum and then fell. Possibly the subsidence of the froth was associated with the uprising air—an effect that has been noted previously in connexion with air-stirring.

High rate. Results of a typical experiment are shown in Fig. 4. The

rate of application of foam was in this case 3·4 g.p.m. (expansion 8·2 to 8·6), and, following a pre-burning period of 24½ min, extinction was effected in 2¾ min. The main differences of behaviour as compared with the low-rate experiment were that froth appeared still to be building up when extinction occurred, and the hot-zone temperature at the time of extinction was not 130° C but considerably lower (about 65° C).

Discussion.

Top application.

The results of the experiments described suggest that the extinction of fire by foam does not take place by the same mechanism with all grades of oil. We may, in fact, distinguish four classes of oil for the present purpose, namely those in which :—

(1) the surface temperature during burning is below 100° C;
(2) the surface temperature during burning is above 100° C, but no hot zone is formed, and the extinction temperature is below 100° C;
(3) the surface temperature is above 100° C and no hot zone is formed, but the extinction temperature is also above 100° C;
(4) a hot zone is formed at a temperature above 100° C.

With type (1), exemplified by benzole and motor spirit, a blanket of foam can begin to build up on the liquid surface from the first application. On account of flame radiation the foam blanket tends to a temperature of 100° C, and therefore can exert little cooling effect on the surface. However, as has been shown in air-stirring experiments, with benzole and motor spirit surface cooling, even to atmospheric temperature, has little effect on the burning rate so long as the surface remains exposed to flame radiation. In these instances, therefore, it seems that extinction is dependent upon the formation of a coherent blanket which protects the surface from radiation and also mechanically impedes the evaporation of the fuel.

With type (2), exemplified in the present experiments by gas oil, the foam first applied is broken down by contact with the hot surface, but cools it in the process to 100° C or less, when a stable blanket can begin to form. The initial interaction of foam and hot oil results in the formation of a thin layer of froth. Since the surface must be cooled well below 100° C for extinction to occur (as shown in air-stirring experiments with gas oil) and the foam (as with type (1)) is unable to perform this duty, extinction is finally effected by blanketing.

With type (3), exemplified by Pool lubricating oil, grade 20, the foam first applied is destroyed by and cools the hot surface, with slight froth formation. Since, however, the extinction temperature is well above 100° C the fire is extinguished during this cooling process and before a stable foam blanket has begun to form. The blanket is, in fact, formed only if foam application is continued after extinction has taken place. It is interesting to reflect that with this type of oil, the spread of the foam is probably not important, for if the surface is cooled at one point, convection will tend to spread the cooling effect over the surface. With a viscous grade this effect might be impeded, but not so with some of the lighter lubricating oils, which will also have high extinction temperatures.

With type (4), exemplified by fuel oil, not only is the surface temperature above 100° C, but there is also underneath a substantial reservoir of hot oil. As a result, not only is foam rapidly broken down at the oil surface, but also no appreciable amount of liquid water escapes volatilization in the hot zone. The whole function of the foam is thus to cool the hot zone, whereby marked frothing results. There is no question of the formation of a foam blanket at any time during the process of extinction.

The flames finally disappear when the hot-zone temperature reaches about 130° C. It was shown in the earlier investigation [1] that when the hot zone is cooled by the introduction of cold oil, flames are largely cleared from the surface at this temperature, but that the effect is usually only partial and temporary. If, however, stirring is carried out in such a way and with such vigour that the surface temperature is also reduced to this level, permanent clearance of flames results. In these circumstances the temperature of the bulk of the hot zone is usually much lower.

It is clear from this earlier work that, with this particular grade of oil, final extinction depends on cooling the hot zone, *including the surface layer*, below 130° C, and foam applied from above may operate simply in this way. An alternative is, however, possible, namely that extinction by foam really corresponds with the " temporary " effect observed when cooling by stirring, but that due to the presence of water or the rise in level due to frothing, the residual " edge fire " is in some way extinguished, and rekindling cannot occur.

Base application.

During base application stirring naturally plays a part. Thus, with fuel oil, the cooling of the hot zone necessary for extinction is partly due to dilution with the underlying cold oil. That the water present also assists in the cooling action is demonstrated by the occurrence of frothing.

When the foam is applied sufficiently slowly, extinction occurs at a hot-zone temperature of about 130° C just as with top application. When, however, the rate of application is more rapid the hot-zone temperature falls considerably below 130° C before extinction occurs. The analogy with simple air stirring is clear and suggests that with low foam rates extinction is, indeed, a case of the " temporary " effect made " permanent " due to the presence of water. At high foam rates, however, as with high stirring rates, the " temporary " phase becomes so abbreviated as to be inappreciable, and extinction awaits cooling of the surface layer from below (in the face of flame radiation) to the temperature of 130° C.

Although qualitatively, stirring and base-applied foam give such similar results, one would expect quantitative differences in that the presence of water, by virtue of its cooling action, should reduce the requirement of air to reach any particular stage in the cooling of the hot zone. This aspect amongst others, receives further consideration in Part II.

PART II. COMPARISON OF TOP AND BASE APPLICATION TO POOL FUEL OIL.

By J. H. Burgoyne and J. F. Richardson.

Introduction.

The mechanisms of extinction of burning Pool fuel oil by top and base application of foam have been discussed in general terms in Part I. It has been shown that cooling of the hot zone is the material operation and that when this is accomplished by foam, and probably by any medium involving liquid water (*e.g.*, water sprays), frothing may be anticipated.

It is to be expected that the depth of froth produced will increase with increasing depth of hot zone (*i.e.*, increasing time of burning). Thus it has been recognized in the past that, in given circumstances, there is likely to be a certain period of burning after which the application of foam will lead to froth formation in excess of the ullage available in the tank, and thus result in slopover.

It is also to be expected that the rate of froth formation will be related to the rate of foam application, and to the properties of the foam. It is therefore possible that, in certain circumstances, foam application could be so controlled as to extinguish a fuel-oil fire and yet keep frothing within the bounds of the available ullage. In order to form any opinion on this issue, however, a quantitative development of the experiments on fuel oil described in Part I is necessary, so that foam requirements for extinction can be correlated with the manner and rate of foam application, foam characteristics, period of burning, and the amount of froth formation. The experiments described in the following sections were undertaken as a contribution in this respect. They are limited in scope in that they refer only to one scale of operations (the same as in Part I), but they go far enough to indicate the relations existing between the factors mentioned. An examination of scale effects could be made should data be required for large storage tanks.

Experimental Arrangements and Procedure.

The general experimental arrangements are illustrated in Fig. 5. The burning tank was especially constructed and set up to withstand repeated slopovers. It was of the same diameter as the tank referred to in Part I (22 in), but it was more robustly constructed (of $\frac{1}{4}$-in steel) and had a dished bottom giving a depth of $41\frac{1}{2}$ in at the centre. It was fitted with a substantial steel "collar" to throw burning oil clear of the sides, and thermocouples could be inserted through glands in the walls at 6-in intervals, although they were used only in preliminary assessments of the burning behaviour of the oil and were then replaced by plugs. The tank was provided with thermal lagging.

Foam could be delivered to the tank either by a 1-in overhead pourer (shown by broken lines in Fig. 5) or through a 1-in pipe connected to the 2-in product inlet line of the base. The overhead pourer was arranged with a swivel joint so that the foam could be set running, adjusted to the

desired rate and quality, and then applied to the fire by swinging the pipe. The base-injection line incorporated an inverted U-tube to prevent oil flowing back into the foam generator, and the lowest points on the line were fitted with drain cocks. When foam was to be applied by base injection, its rate and quality were measured as it issued from the open end of a rubber hose, and connexion to the supply line to the tank was then made when required. In all cases the foam properties were checked after the completion of the experiment. The methods of generation and measurement of the foam were as described in Part I : the generator and controls were separated from the burning tank by a brick wall.

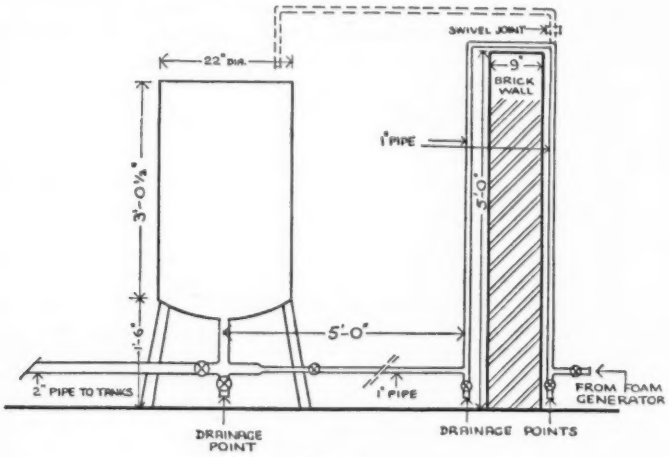

FIG. 5.

DIAGRAM OF APPARATUS.

Oil was drawn from a standard stock in a 6000-gal tank. Since a fresh quantity of oil had to be used for each of the many experiments, considerable emphasis was laid upon rapid filling and emptying of the tank. Fresh oil was admitted from storage by gravity feed using large-diameter pipelines and a substantial pressure head, and after each experiment the oil–foam mixture was withdrawn, by a pump of ample capacity, to a settling tank where, after drainage, a very substantial recovery of oil was made. In between experiments the burning tank was cooled by hosing down and was allowed to dry before admitting the fresh oil. A sample of the oil actually in the burning tank before each experiment was withdrawn for check analysis, and where this showed irregularities (usually abnormal water content due to wet pipelines, etc.) the experimental results were rejected.

Preliminary burning tests (without any application of foam) were carried out on the standard oil with thermocouples in place to determine the absolute rate of downward movement of the boundary between the hot and cold zones. In a further experiment, the rate of fall of the oil surface during burning was measured and the net rate of formation of hot zone was

then calculated. These results were employed in the subsequent experiments to estimate the depth of hot zone formed after measured periods of burning.

Experiments were carried out on the application of foam both by top pourer and through the base. In each case, for a few selected times of burning, the effects of foam rate and quality on the time for extinction and on the maximum amount of frothing (except when slopover occurred) were observed. The maximum amount of frothing could be determined by inspecting the inner wall of the tank immediately after extinction of the fire. In all top-application experiments a very clear mark remained, indicating the highest level of the froth, since the maximum frothing occurred just before extinction (see Part I). This was also the case with high rates of base application but with base application at low rates the maximum frothing occurred relatively early, and subsequent burning tended to obscure the mark.

The specification of the oil used fell within the following limits :—

Specific gravity at 60° F	0·930–0·937
Viscosity (Redwood No. 1) at 100° F	190–250 sec
Flash point	Above 160° F
Water content	<4·0 per cent.

Experiments on oils whose analyses fell outside these limits were ignored in compiling the results.

Results.

Preliminary tests.

Preliminary experiments, with thermocouples in use, revealed some variation on different occasions, in the rate of hot-zone formation and in the hot-zone temperature. This is in accordance with previous experience and can be attributed largely to variable weather (mainly wind) conditions. Under the conditions selected for the foam experiments (ullage of 20 in or more to allow for frothing) the hot-zone temperature was about 340° C, and its lower boundary fell at a rate of between 11·5 and 12·5 in/hr. The oil surface fell at a rate of about 0·75 in/hr.

In all the preliminary tests a spontaneous eruption of oil finally terminated the experiment in spite of the fact that no water, apart from that initially contained by the oil, had been admitted to the tank. In most cases the hot zone had probably approached the tank bottom, and the occurrence could therefore be described as " boilover." In two cases, however, the eruption occurred at a much earlier stage. Since analyses of the relative oil samples showed no moisture content greater than 0·65 per cent, there is foundation for the belief that slopover can be caused by a local high water content or some other circumstance not revealed by normal sampling and analysis. It may further be expected that abnormal frothing may occur from time to time, even in burning experiments in which a " standard " stock of oil is used.

Top application of foam.

(a) *Requirement for extinction.* In Fig. 6 the ratio of the time of burning (which was 15, 30, or 50 min) to the time required to effect extinction is plotted against the weight rate of application of foam. It is seen that although there is scatter, the points fall about a single curve, irre-

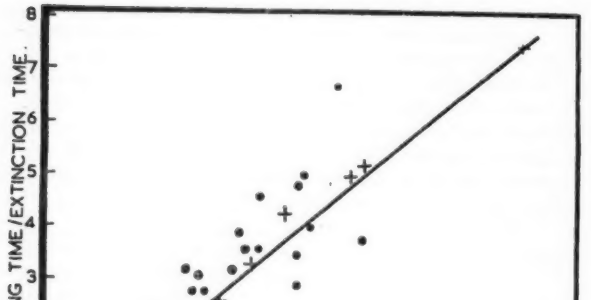

FIG. 6.

RELATIONSHIP BETWEEN BURNING TIME, EXTINCTION TIME AND FOAM (TOP) APPLICATION RATE.

+ 15 min burning.
● 30 min burning.
⊕ 50 min burning.

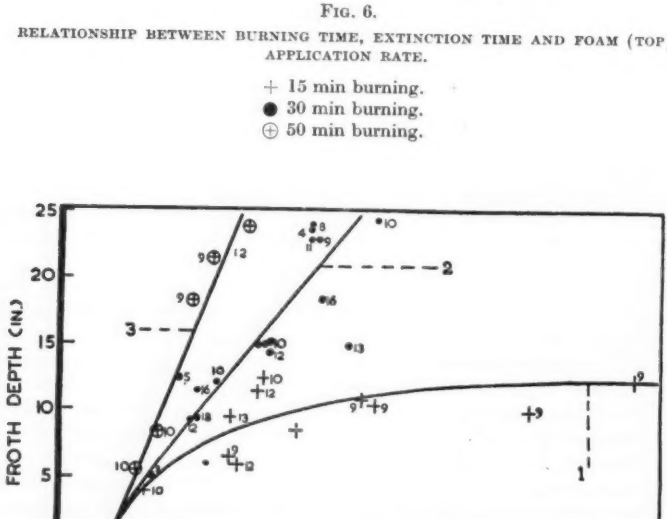

FIG. 7.

RELATIONSHIP BETWEEN MAXIMUM RISE OF LEVEL DUE TO FROTHING AND FOAM (TOP) APPLICATION RATE. BURNING TIMES : CURVE 1—POINTS + —15 MIN, CURVE 2—POINTS ● —30 MIN, CURVE 3—POINTS ⊕ 50 MIN.

Figures near points denote foam expansion value.

spective of the actual time of burning and of the foam expansion. Moreover, for application rates greater than 1 lb/min, the relationship is approximately linear. At rates below 0·6 lb/min the fire was not extinguished.

(b) *Frothing.* In Fig. 7 the maximum rise in oil level due to frothing is plotted against the weight rate of foam application for three separate series of experiments in which the burning times were 15, 30, and 50 min. For each series the points, though scattered, lie about a single curve, and there is no indication of any systematic variation due to expansion (denoted by numbers against the points) which, especially in the " 30-min " experiments was purposely varied widely. In each of the three series of experiments, application of foam at a rate below about 0·4 lb/min appeared to produce no frothing.

In each series the maximum amount of froth produced increased with increasing rate of application of foam (*i.e.*, of water), and at any given rate the amount of froth was greater for the longer burning periods. The " 30- and 50-min " curves were limited in extent by the inability of the tank to contain more than about 24 in of froth, but the " 15-min " curve shows that at high application rates the depth of froth reaches a limiting value for a given depth of hot zone. At rates above about 6·5 lb/min it was found that white foam built up on the oil surface due to the inability of the hot zone to assimilate it completely.

A comparison of the results with those obtained in the experiments described in Part I seems to indicate that the actual depth of froth produced is somewhat dependent on the construction of the tank.

Base application of foam.

(a) *Preliminary experiments.* A few preliminary experiments were carried out to examine the effect on the foam of its upward passage through certain depths of cold fuel oil in the experimental tank. The results showed that both the amount of water and the character of the dispersion emerging on the surface of the oil were extremely variable. The matter calls for further study under controlled conditions, for the apparatus in use was unsuited for such study, and it could only be concluded that the results of base-application experiments with burning oil, both as regards requirements for extinction and the amount of frothing, might show divergencies due to variations in the quantity and character of the foam actually reaching the hot zone from below.

(b) *Requirement for extinction.* It was found that for a given time of burning, the time for extinction increased with decreasing rate (weight basis) of application of foam. Below a certain rate, extinction could not be effected at all. With a time of burning of 15 min and foams having expansion factors in the neighbourhood of 10 this limiting rate was about 0·15 lb/min, which corresponded with a volume rate of about 0·025 cu. ft/min. However, expansions were not varied widely in these experiments, and it is not possible to say whether the weight (cooling by water) or volume (stirring) rate is the more significant in fixing the limit.

It is clear, however, that the respective minimum rates quoted are about 25 per cent, both of the minimum foam requirement for extinction by top application and of the air requirement for extinction in similar circumstances by stirring alone.

In Fig. 8, the ratio of the time of burning to the time required to effect extinction is plotted against the weight rate of introduction of foam (water) into the tank. The expansion of the foam as generated is indicated by numbers against the individual points. The interpretation of Fig. 8 receives further consideration at a later stage.

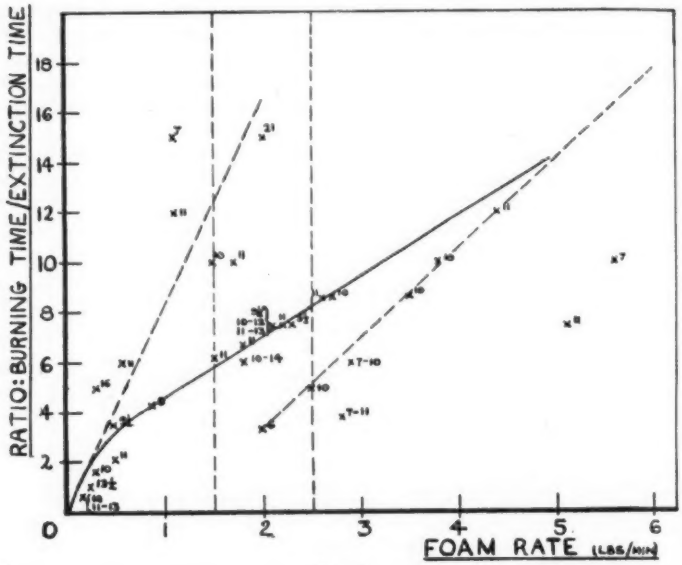

FIG. 8.

RELATIONSHIP BETWEEN EXTINCTION TIME AND FOAM (BASE) APPLICATION RATE. BURNING TIME 15 MIN.

Figures near points denote foam expansion value.

(c) *Frothing.* In Fig. 9 (Curve 1) the maximum increase in depth due to frothing is plotted against the weight rate of introduction of foam for experiments in which the burning period was 15 min. The points indicate a relationship quite different from that found in connexion with top application (Curve 2). In the first place, there is appreciable frothing (2 to 3 in) with air stirring alone (weight rate = 0) and the curve accordingly intercepts the " depth of froth " axis. At the lower foam rates the frothing resulting from base application is similar to, or even less than, that with top application; but at about 2 lb/min the amount of froth rises very sharply and reaches a value nearly twice that for top application and representing an eightfold increase in the depth of the hot zone. It is possible that the increase might have been slightly more but for the fact that this amount of frothing just reached the rim of the tank and became subject to increased air currents. Foam expansion is seen to have little effect on the depth of froth production.

A certain number of experiments were carried out in which the burning

period was 30 min. In almost every instance the base application of foam led to persistently repeated slopovers, which continued until most of the oil had been ejected from the tank. This spectacular result was ultimately found to be due to the fact that the resultant oil temperature on completely mixing the hot and cold zones together was, with this period of burning, well in excess of 100° C.

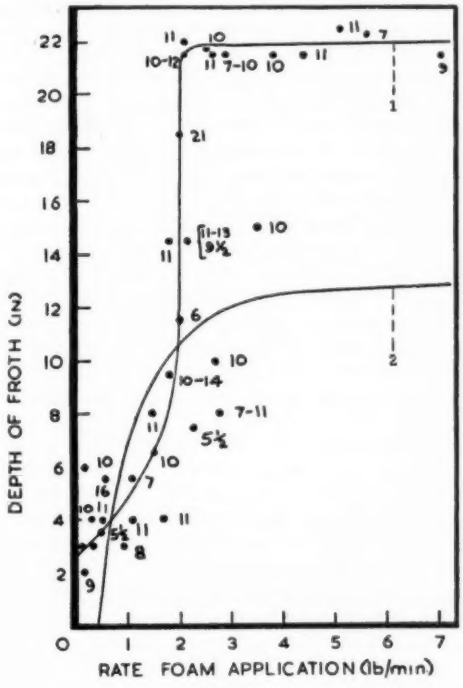

FIG. 9.

RELATIONSHIP BETWEEN MAXIMUM RISE OF LEVEL DUE TO FROTHING AND FOAM APPLICATION RATE. BURNING TIME 15 MIN.

Curve 1—and all points-base application; figures near points denote foam expansion value. Curve 2—top application, copied from Fig. 7.

DISCUSSION.

It was concluded in Part I that the extinction of burning Pool fuel oil depends on cooling the hot zone and surface to a temperature below about 130° C. In the case of the top application of foam, one would therefore expect the time required for extinction to be approximately proportional to :—

(1) the difference between the hot-zone temperature and 130° C;
(2) the time of burning (*i.e.*, the depth of hot zone);

(3) the reciprocal of the weight rate of application of water or foam, after allowing for that required to balance the input of heat from the flames to the hot zone.

The first of these relationships was not examined in the investigations described. The second is substantiated quite well by the coincidence of points corresponding to different pre-burning times in Fig. 6, and the third by their essentially linear distribution. The minimum application rate that would effect extinction was about 0·6 lb/min, which is equivalent to the extraction of heat from the oil at a rate of about 380 lb. cal/min. It has been found in other experiments on Pool fuel oil, in a tank of similar area, that during normal burning the total rate of transmission of heat to the oil is about 390 lb. cal/min. The agreement between these two figures indicates that it is only when the foam is applied at such a rate that it can absorb heat from the oil faster than this that extinction can be effected simply by cooling the hot oil.

Clark, Thornton, and Lewis [3] have shown that the rate of control of petrol fires by the top application of foam is also a linear function of the rate of application of water. In view of the results described in Part I of this paper the explanation can hardly be precisely the same as in the case of fuel oil. Rather must it lie, in the case of petrol, in a relationship between the rate of application of water and the absorption of radiant heat from the flames.

The extent of frothing also increases with the rate of application of water from the top pourer, but not linearly, and a limiting depth of froth is reached at high application rates. This limiting depth is probably roughly proportional to the hot-zone depth when this is not too shallow. In the experiments actually carried out the hot zone was shallow, and the limiting depth of froth increased more rapidly with hot-zone depth than a linear relation would imply. After 15 min burning the maximum increase in the volume of the hot zone due to frothing was fivefold, but after 30 min burning this ratio was certainly exceeded. This is presumably because the rate of destruction of froth is independent of its depth, being caused mainly by radiation from the flames.

Neither the time of extinction nor the degree of frothing appear to depend upon the character of the foam *reaching the hot zone*. Expansion, dispersion, and other characteristics of foam determine its stability, but since, when foam is applied to fuel oil from above, it exercises its function only by breaking down, stability does not matter. It must be emphasized, however, that, in practice, foam characteristics might influence the fate of the foam on its way to the oil surface, and hence determine the amount of water reaching the hot zone. In this sense foam stability might be important.

The question of what happens to the foam on its way to the hot zone is a very significant one when application is through the base of the tank. It is known that the passage of the foam up through the cold oil causes a certain amount of breakdown, but the factors concerned need detailed investigation. In the present work the character of the foam introduced was not allowed to vary widely, but even so and with the comparatively shallow depths of oil traversed, there was evidence at times of considerable variation in the character of the foam emerging into the hot zone.

In base application, however, the air phase of the foam plays an important part in stirring the hot and cold zones together, and it is the consequent cooling effect on the hot zone, together with more or less of assistance from the water present, that is responsible for extinction by this method. The stirring element in base application must always be present, but, as previous work on air-stirring has demonstrated, the presence of water in the dispersion is not necessary to effect extinction if the resultant temperature due to mixing the hot and cold zones does not exceed about 130° C.

The apparatus as arranged for these experiments did not permit an accurate record to be made of the time of commencement of the application of foam, since it had to sweep out the air and oil in the delivery line before it could enter the tank and thereby caused a preliminary stirring action. Further, particularly at low rates of application, the foam probably underwent some destruction in contact with the oily walls of the tube, and a proportion of water was probably introduced unassociated with air.

It has been shown in Part I that, under the conditions of experiment, there is probably a difference in the mechanism of extinction at high and at low rates of foam application. At low rates, extinction occurs at a hot-zone temperature of about 130° C (as with top application), but at high rates it is postponed until a considerably lower temperature is reached. This knowledge enables a certain interpretation to be put upon the apparently rather scattered distribution of points in Fig. 8.

Let the diagram be divided into three strips, as indicated, corresponding to the following ranges of foam-application rate :—

(1) 0 to 1·5 lb/min.
(2) 1·5 to 2·5 lb/min.
(3) Above 2·5 lb/min.

If points in these three regions are now considered separately, it is seen that those in the first and third lie reasonably well about straight lines (shown broken) which both terminate at about 2 lb/min. Those in the second zone are scattered, but lie between the extensions into that zone of the two broken lines. The results are therefore consistent with the view that there are, in the ranges below and above 2 lb/min respectively, two separate frothing systems; and that between 1·5 and 2·5 lb/min behaviour is transitional between the two systems, resulting in a much greater variation in the extent of frothing for a given foam-application rate than is otherwise experienced.

The minimum volume rate of foam application (air flow) to achieve extinction under the conditions of experiment was about 0·025 cu. ft/min. Air flows of this order would be expected, from previous work, to cause a temporary flame clearance of appreciable duration. It seems then that under these conditions the presence of a little water (one quarter of that for extinction by foam alone) suffices to make the partial and temporary effect complete. At the higher flow rates duration of the temporary effect is inappreciable, but permanent clearance of flame is subsequently effected by stirring action alone. At about 2 lb/min foam rate there is a sharp rise in the maximum extent of frothing (Fig. 9, Curve 2) and it is possible that this may be connected with the relative delay resulting from the change-over from one extinction mechanism to the other.

At low foam rates the extent of frothing was of the same order as for top application. The limiting extent of frothing at high foam rates was, however, about double that for top application. The reason for this is probably that, in base application, froth formation is initiated from the bottom of the hot zone so that less steam escapes from the liquid phase than when foam is poured on from above and is immediately subjected to the destructive action of radiant heat from the flames. It has already been mentioned that there is a limit to the rate at which the hot zone can assimilate foam via the surface.

It appears that if the period of burning is such as to give a mixed hot/cold zone temperature above 100° C frothing is particularly severe because it is initiated from the very bottom of the tank when the zones have been mixed. It has been observed previously (Burgoyne and Katan [1]) that stirring which does not extinguish the fire markedly accelerates the rate of heat absorption by the oil, and no doubt this characteristic prolongs the period of cooling of the hot zone to below 100° C by base-injected foam. From a practical standpoint these conditions are extremely hazardous and might easily arise in partially filled tanks. If the mixed oil temperature is above 130° C it appears that the temperature has to be lowered to this figure by the water content of the foam before extinction can take place.

Acknowledgments.

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The authors are indebted to The National Oil Refineries, Ltd., for facilities afforded at their Skewen Refinery to carry out all the experiments described. The co-operation of many members of their staff, and especially of Mr E. Thornton, is gratefully acknowledged. Most of the routine analyses of oil samples were carried out in the Refinery test laboratories.

In conducting many of the experiments described in Part II the authors had the assistance of Dr D. J. Rasbash.

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[2] Clark, N. O. Dept. Sci. Industr. Res., 1947, *Chemistry Research Special Rept. No.* 6.
[3] Clark, N. O., Thornton, E., and Lewis, J. A. *J. Inst. Petrol.*, 1947, **33**, 192.

Discussion.

R. R. Lloyd : In the north of England in years past, one or two experiments have been made on tanks of similar size to those mentioned by the authors. As a result of those experiments, a circular was issued, which stated quite categorically that experiments of this nature, on the size of tanks in question, were not indicative of results on very large tanks. I was rather interested to hear this evening that the authors of the paper had used a 40-gal tank, and I am wondering whether the team from the Imperial College could give some indication of how the results of these small-tank tests have compared with those obtained on larger-scale tanks.

DR BURGOYNE: A rough comparison between our experiments on motor spirit and those of Clark, Thornton, and Lewis (*J. Inst. Petrol.* 1947, **33**, 192) using a 9-ft-dia tank is the only one possible at present. They found that for foam of expansion 10 an application rate of 0·25 g.p.m/sq. ft. was just sufficient to extinguish the fire. We find on the 40-in tank that the corresponding figure is about 0·65 g.p.m/sq. ft. We cannot infer much from this regarding really large tanks of motor spirit, but so far as I am aware, even this much information is lacking with regard to the other grades we have studied. Clearly the work should be extended in the direction of larger scales.

A. S. MINTON: It occurs to me that it may be advisable to conduct experiments with a view to distributing the burning oil from the surface to the bottom of a tank, in order to cool it, for it seems that there is quite a possibility of extinguishing a fire, in the early stages at least, in that manner.

DR BURGOYNE: That is quite true; we dealt with the matter in our previous work, which was reported here nearly three years ago. We gave the results of experiments in which the stirring of the cold oil at the bottom into the hot oil at or near the surface was brought about by bubbling air through the bottom and by the use of other mixing methods.

S. HART: In regard to the application of foam, I should like to ask for more information about the ratio lb per min/g.p.m.

DR RICHARDSON: All the results were expressed on the basis of the mass rate of application of foam in pounds per minute, *i.e.*, the rate of application of water to the fire. The translation from pounds per minute to gallons per minute depends upon the expansion ratio of the foam. With an expansion ratio of 1 (*i.e.*, with pure water) 1 lb/min would be 0·1 g.p.m.; if the expansion ratio were 10, then 1 lb/min would be the same as 1 g.p.m.

F. P. MILLS: Can the authors give us their ideas about the merits of air foam and chemical foam respectively on similar fires?

DR BURGOYNE: No, for we have done no work on chemical foam; all this work has been with air foam.

J. H. HUTCHINSON: Until recently fireman have always told me that they are against introducing foam into the base of tanks because they thought they would get "boil-over" rather than "slop-over." Dr Richardson has shown us pictures of occurrences which I should take to be boil-over. Can he tell us the difference, in his experiments, between a slop-over and a boil-over, and can he say whether we should experience a boil-over by introducing water to the bottom of a hot zone?

DR RICHARDSON: I have used the term "slop-over" to denote the expansion of the hot zone by frothing and the subsequent expulsion of burning oil from the containing vessel as the result of adding water to the

hot zone. We have restricted the term "boil-over" to those cases in which the oil has been burning for a sufficient time for the temperature of the whole of the oil in the tank to have been raised to that of the hot zone; the hot-zone boundary then comes suddenly into contact with any water which has collected at the bottom of the tank. In general, the boil-over is a far more vigorous affair than the slop-over, because, by the sudden vaporization of the water, a high pressure may be developed at the bottom of the tank and almost the whole of the contents blown out. The addition of air foam to the bottom of the tank should never cause a boil-over unless the lower boundary of the hot zone has reached the bottom at the time of foam application.

A. P. L. SULLIVAN: Can the speakers say something about the froth? Is it disturbed oil, or an emulsion? If it is an emulsion, how soon does it break down?

Secondly, heavy oil fires were said to be extinguished by cooling and not by blanketing. Does that not indicate we should try to extinguish them by water spray rather than by foam?

DR BURGOYNE: The froth is an oil–water emulsion, formed when the water in some form comes into contact with oil at a temperature above the boiling point of water; so that emulsification is promoted by steam. I would not say that the emulsion is very stable; it does not last very long after the conclusion of the experiments and, of course, there is no doubt that the breaking down of the emulsion is one of the factors involved in the interpretation of the results which Dr Richardson obtained.

With regard to the possible use of water spray in place of foam, I think it is quite correct to contend that the two are more or less equivalent as applied to oil of high surface temperature or of hot-zone-forming character; in other words, it does not matter a great deal in principle whether the water is applied as an overhead water spray or as foam.

G. E. NEVILLE: On the matter of reducing the surface temperature by recirculation of the oil in the tank, have experiments been carried out with refrigeration?

DR BURGOYNE: No. The short paper we shall present next, on the use of solid carbon dioxide, bears a little on that subject. But I think the direct answer to your question is "No."

H. KAYE: How does the height of foam injection above the liquid surface affect frothing, and should we get minimum frothing by injecting the foam at the liquid surface?

DR BURGOYNE: We did not investigate that point; it is one of the variables in normal conditions which we kept constant in our experiments. I think there might be some variation in the extent to which the foam is broken down before arriving at the surface. Therefore, the amount of foam reaching the surface would bear a varying relationship to the amount put in.

J. E. FARRELL: Inasmuch as the use of air has been mentioned for stirring the oil from the bottom of the tank to the top, and Dr Burgoyne has mentioned that the quality of the foam did not appear to make a great deal of difference, I wonder whether there is any change of opinion as to whether or not compressed air could be used, without any foam at all.

DR BURGOYNE: Yes, we feel that the use of compressed air alone is quite a promising line. We did not deal further with the matter in this paper, merely because the purpose of this particular investigation was to look into the problem of control when foam is used.

E. THORNTON: Having spent several hours with the slide rule and in other ways, I should like to congratulate the authors on having put their actual results before us as well as their arguments, because that allows others to look at the matter from another angle; and it is the best way to put the matter forward, because sometimes the significance of minor details is not grasped at the time the work is done.

I think any suggestion which implies escape from the need to counter in some way the radiated heat which keeps the fire going ought not to be taken too seriously: I am sure Dr Burgoyne would agree with this and did not seriously intend to evade the point.

The temperature at extinction is one of the effects of extinction mechanism, and is to some extent accidental in that it cannot be reached until the conditions which have elevated the temperature, *i.e.*, the radiant heat from the flame, have been removed or given some other job to do!

When foam put on overhead is evaporated instead of oil being heated, the radiation is countered and the vapours are not produced, so the fire goes out.

When any oil is circulated rapidly, the radiation is absorbed in a lot of oil so that none gets hot enough to give vapour and the fire goes out. This is true for any oil, but different oils will have different temperatures at the point when vapour *production* ceases.

There is, however, something beyond this factor coming into play in the case of base injection on this scale. The quantities used in this work would do half the job if they acted in the same way as stirring and supplying water as foam overhead at the rates used.

What is the new factor involved? Is it connected with extinction by steam as a flame inhibitor?

THE AUTHORS: Under the conditions of experiment, the minimum *volume* rate of foam application by base injection to achieve extinction of fuel oil was about 0·025 cu. ft/min. This rate of application of air, as a stirring agent, would cause temporary flame clearance and a residual edge-fire. Evidently the presence of a little water with the air (as foam) suffices to finish off this edge fire. The function of the water in this case is not quite the same as when foam is applied from above, and we do not think, therefore, that any special significance attaches to the ratio of the rates of application of water in the two cases.

The following paper was then read:

THE USE OF SOLID CARBON DIOXIDE TO EXTINGUISH THE BURNING OF LIQUIDS.

By J. H. BURGOYNE,* L. L. KATAN,* and J. F. RICHARDSON.*

SUMMARY.

The utility of solid carbon dioxide as an extinguisher of fires involving liquids in bulk has been examined. The mode of action of the CO_2 depends upon its state of division. Powdered material, and in some cases small lumps, float on the burning liquid and cool the surface. In these circumstances the effectiveness of the application is, broadly, increased as the liquid-surface temperature (final boiling point) and extinction temperature (which is closely related to the fire point) are greater, provided that a hot zone is not formed. Larger grades of solid CO_2 sink in the inflammable liquid, and their evaporation causes an effect similar to that of air-stirring. Liquids of high surface temperature and those which form a hot zone are more effectively treated by this method than by the surface application of fine material, except that an edge-fire may be left which requires extinction by auxiliary means.

INTRODUCTORY.

IN the extinction of burning of a liquid by addition of a non-inflammable material, three factors may be concerned :—

(1) suppression of flame by incombustible gas or by vapour derived from the extinguisher;

(2) dissolution of the extinguishing liquid in the surface layer of the burning liquid, leading to diminution in the rate of evolution of inflammable vapour and replacement by non-inflammable vapour;

(3) cooling of the surface layer of the burning liquid and of the hot zone, if formed, leading to diminution in the rate of evolution of inflammable vapour.

In the light of these principles solid carbon dioxide is a material of more than ordinary interest, for it is capable of considerable heat absorption at low temperatures, in the process of which it gives rise to a gas with flame-suppressing properties.

With considerations such as these in view a general investigation was undertaken to examine the utility of solid carbon dioxide as an extinguisher for the burning of liquids and to determine the best method of application in relation to the character of the liquid concerned. It has been recognized in an earlier publication [1] that the volatility of the inflammable liquid and the question of whether or not it forms a hot zone are crucial factors, especially where extinction is to be effected by cooling methods. The main purpose of the present work was to examine the effect of solid CO_2 on inflammable liquids differing in these respects.

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Experimental.

Experiments with industrial spirit.

As a result of a number of preliminary experiments it was established that the total weight of pulverized solid CO_2 required to extinguish, in a single application, a fire involving industrial spirit was independent of the depth of liquid used, but increased with the area of the burning surface and with the time of burning before application of the extinguisher. It was observed that powder and small lumps of solid CO_2 floated on the surface, but that lumps greater than about 3 g in weight sank. In the latter circumstances the mechanism of extinction was evidently changed, and much greater applications of extinguishing material were necessary.

The effect of the initial burning time is shown in Table I, from which it appears that conditions became fairly stationary after 20 min burning, but within this period the requirement of extinguisher became greater with

Table I.

Effect of Preliminary Burning Time of Industrial Spirit on Requirement of Solid CO_2 (2- to 3-g Lumps) for Extinction.

1-ft-diameter vessel.

Time (min).	Requirement of solid CO_2	
	g.	g/sq. ft.
0·5	12– 17	15– 22
5·0	50– 75	65– 95
15·0	70–100	90–130
20·0	100–120	130–150
30·0	95–120	120–150
60·0	95–120	120–150

longer times. This effect may be attributed partly to the establishment of a temperature gradient beneath the burning surface and partly to the attainment of a stationary temperature distribution in the walls of the containing vessel. Experiments previously described [1] suggest that with a fairly pure liquid of low boiling point the temperature gradient in the liquid is quickly attained, and it therefore seems likely that the effect shown in Table I was chiefly due to heating up the containing vessel. As it was desired to study the effect of solid CO_2 in extinguishing burning of the liquid rather than in cooling the vessel walls, experiments to show the effect of the burning area and the lump size of the solid CO_2 on the requirement of the latter for extinction were carried out with such a short preliminary burning period (30 sec) that the walls had little time to heat up. The results of these experiments are summarized in Table II, from which it appears that the requirement of 2- to 3-g lumps (which float) per unit area probably increases with area up to about 3 sq. ft., but increases much less thereafter. The requirement of powder is a little less, but that of 10 to 20-g lumps (which sink) is much more.

In order to distinguish the separate " cooling " and " inert-gas " effects involved in the use of solid CO_2 in this way, an experiment was carried out

TABLE II.

Effect of Burning Area (Circular) of Industrial Spirit on Requirement of Solid CO_2 for Extinction.

30 sec preliminary burning.

Diameter of vessel, in.	Surface area, sq. ft.	Weight of solid required.					
		Powder.		2–3 g-lumps.		10–20 g-lumps.	
		g.	g/sq. ft.	g.	g/sq. ft.	g.	g/sq. ft.
4·24	0·097	2– 3	21–31	2– 3	21–31	*	*
8·75	0·418	8– 10	19–24	6– 12	14–29	50–100	120–240
12·0	0·786	8– 12	10–15	12– 17	15–22	30– 50	38– 64
24·0	3·14	75–100	24–32	100–125	32–40	200–300	64– 96
49·0	12·56	†	†	450–500	36–40	*	*

* Not determined.
† 400 g (32 g/sq. ft) was not quite effective, but it appeared that it could be so applied sufficiently rapidly.

using the 8·75-in-diameter vessel (see Table II) in which gaseous CO_2 was released from a four-point distributor 1½ in below the liquid surface. Under the conditions of initial temperature and burning time given in Table II a delivery of 0·8 cu. ft/min of gas was necessary to cause extinction. By applying the solid CO_2 to the unignited spirit in the same vessel, measurements were made of the maximum rate of gas evolution (calculated at N.T.P.) corresponding to the conditions for extinction indicated in Table II. The results were as follows:—

For 6 to 12 g of the 2- to 3-gm lumps . . . 0·135 ± 0·045 cu. ft/min.
For 50 to 100 g of the 10- to 20-g lumps . . 0·9 ± 0·3 cu. ft/min.

It is thus clear that while the effect of the submerged (large) lumps can be accounted for substantially in terms of the evolution of inert gas, it is necessary to suppose that the effect of the floating material is mainly due to its ability to cool the surface of the burning liquid. It is already known that simple stirring of a liquid as volatile as industrial spirit could not lead to extinction, and it now seems, moreover, that the use of submerged solid CO_2 to effect the stirring does not result in any useful cooling of the surface to sub-atmospheric temperatures by indirect means.

Experiments with other low-flash-point liquids.

The results of similar tests in the 8·75-in-diameter vessel using liquids having flash points in the range −40° to +25° C are summarized in Table III, in which the relevant figures for industrial spirit are included for comparison. Except in this latter case and in that of amyl acetate, the 2- to 3-g, as well as the large sizes of solid CO_2, sank and therefore did not operate primarily by surface cooling. Lumps submerged in benzene caused solidification of the fuel, which retarded the evaporation of CO_2; and this undoubtedly accounts for the abnormally high requirement of 2- to 3-g lumps. Otherwise, rates of evaporation did not vary much, and it is seen from Table III that, with decreasing flash point of the inflammable

liquid, increasing quantities of solid CO_2 were required for extinction. For petrol, such large amounts were needed as to lead to violent splashing of the burning liquid.

TABLE III.

Requirements of Solid CO_2 to Extinguish Various Liquids.

8·75 in dia vessel. 30 sec preliminary burning.

Inflammable liquid.	Approx flash point, ° C.	Boiling point, ° C.	Specific gravity.	Max lump weight for flotation, g.	Application of solid required, g/sq. ft.		
					Powder.	2–3-g lumps.	10–20-g lumps.
Amyl acetate (at 35° C) . .	25	148	0·88	2	†	5–7	†
Industrial spirit (at 20° C) .	14	78·5	0·79	2·5–3	19– 24	14– 29	120–240
Benzene . .	−11	80·1	0·88	0·5	24– 72	300–360§	†
Acetone . .	−19	56·5	0·79	0·5	24– 84	c 72	c 120
n-Hexane . .	−26	69·0	0·66	0·5	72–215	96–240	†
Pool petrol .	−40	c 40 *	0·74	0·5	‡	†	c 720
Aviation spirit .	−40	c 35 *	0·71	0·5	‡	240–480	†

* Initial boiling point in these cases.
† Not determined.
‡ 191 g/sq. ft. ineffective; 215 g/sq. ft. caused liquid to spill over.
§ Probably high due to freezing of benzene.

Experiments with gas oil.

Whereas, with liquids having a flash point of the order of atmospheric temperature or below, solid CO_2 was a more effective extinguisher when applied in such a form as to float rather than to sink, with higher-flash-point liquids the reverse was found to be true. Thus, with kerosine (flash point 43° to 45° C) burned for 5 min in the 8·75-in-diameter vessel the minimum requirements for extinction were :—

30 to 40 g of powder (floating) (72 to 96 g/sq. ft.).
20 to 30 g of 2 to 3 g lumps (submerged) (48 to 72 g/sq. ft.).

With Pool gas oil (flash point approximately 73° C), burned for 15 min in an 11-in-diameter vessel, the difference was still greater, and the requirements were :—

100 to 150 g of powder (floating) (150 to 230 g/sq. ft.).
20 to 25 g of 10-g lumps (submerged) (30 to 40 g/sq. ft.).

It was known from earlier experiments that with petroleum fractions having a fairly wide boiling range, such as kerosine and gas oil, a fair period of burning (10 to 20 min) is required to establish the stationary temperature gradient below the surface. For this reason it was not considered permissible to make experiments with very short preliminary burning periods. With gas oil, the 15 min allowed was adequate, for in experiments with a 70-min burning time the requirements of solid CO_2 given above were not appreciably increased.

The long burning period led, however, to a considerable heating up of the walls of the containing vessel, which rendered the results with these higher-flash-point liquids difficult to compare with those, already given, obtained after short burning periods with more volatile fuels. For the same burning period, however, the requirements of powder shown above in relation to kerosine and gas oil are of the same order as would be required for industrial spirit. Thus, the extinguishing requirement of surface-applied solid CO_2 does not greatly change as the flash point of the liquid rises above atmospheric temperature.

With submerged solid CO_2, extinction was evidently due to the stirring action of evolved gas, which projected the cold liquid into the burning surface, thereby cooling it and effecting extinction in the manner dealt with at some length in a previous communication.[1] Here, however, extinction, when it occurred, was preceded by a definite period during which, although the surface was clear of flame, an edge-fire persisted for some time. It has been shown that such an edge-fire is maintained by the heat content of the vessel walls, which are not very easily cooled simply by stirring the liquid. With larger vessels the difficulty is greater, and extinction of the edge-fire by stirring may become a prolonged affair if not a matter of pure chance. In these circumstances auxiliary means of extinction would generally be desirable. This would be especially so where stirring was by submerged CO_2, since the stirring has only a limited duration, depending on the size of the lumps used; and the rate of gas evolution falls off as the lumps get smaller through evaporation. If the lumps were to become exhausted before the extinction of the edge-fire, flames would re-spread across the liquid surface. Thus, although submerged solid CO_2 is an effective extinguisher for gas oil in small vessels because extinction of the edge-fire readily ensues after clearance of the surface, it would probably be of practical use in larger vessels only provided auxiliary means were employed promptly to deal with the edge-fire after clearance of the surface. It should be stressed, of course, that such "auxiliary means" would be small in magnitude compared with the measures necessary to deal with the fire in its initial condition before surface clearance.

Measurements of the rate of evaporation of the appropriate-sized lumps of solid CO_2 submerged in gas oil indicated that the minimum rate of evolution of CO_2 necessary to clear flames from the liquid surface was similar to that required using air under the same conditions. There was thus no evidence either that air, as a supporter of combustion, made the fire more difficult to extinguish, or that carbon dioxide, as a suppressor, made it easier to extinguish when the gases were used as stirring media.

An experiment was carried out with gas oil burning in a 22-in-diameter tank, fitted with sub-surface thermocouples, for the purpose of following changes of temperature distribution during the process of extinction by submerged solid CO_2. It was ascertained by this means that the mechanism is precisely similar to that when air is used for stirring. As the latter has been demonstrated in a previous publication [1] no details are required here.

Experiments with Pool fuel oil.

Preliminary experiments were carried out using 11-in-diameter drums, in which a depth of 12 in of Pool fuel oil was burned until the ratio of hot-

zone depth (measured by temperature-indicating paint on the outside of the drum) to that of the residual cold oil was 0·4. Under these conditions the fire could be extinguished by the addition of 25 to 50 g of solid CO_2 in the form either of approximately 10-g lumps or as a single lump. 50 g of powdered material, however, floated on the surface and had very little effect on the intensity of the fire.

When extinction was effected by the use of submerged lumps it was preceded by a period, as in the case of gas oil, in which the surface was free from flame apart from an edge-fire. The use of a 25-g lump of carbon dioxide under the conditions outlined above led to surface clearance, but did not extinguish the edge-fire. The further addition of 25 g of powder at this stage did, however, complete extinction, so that this form of the solid may be regarded as one of the possible " auxiliary means " needed to extinguish the edge-fire.

With greater periods of preliminary burning leading to ratios of hot : cold oil depths of 2 and ∞ (cold oil wholly assimilated) it was found that the fire could not be extinguished with submerged lumps of CO_2 (although much reduced in the former instance), and there was a marked tendency towards frothing and slopover when they were added. This result is in accordance with experience with air-stirring, where it was found that a hot : cold ratio of more than about 0·4 rendered extinction by stirring impossible.

Further experiments with the 22-in-diameter tank fitted with sub-surface thermocouples showed that the effect of the evaporation of submerged solid CO_2 was similar to that of air stirring, and that the necessary rates of gas evolution for control of the fire were similar in the two cases. Hence, neither the flame-suppressing character of the evolved CO_2 nor the heat-absorbing capacity of the solid was of any importance compared with the stirring action of the evolved gas. On this larger scale there was a marked tendency to slopover if too much solid CO_2 were added initially. To avoid this it was found that a small amount had to be added first, followed by the main bulk when the tendency to frothing had subsided. A similar tendency was experienced with air-stirring when the air was suddenly turned on at full rate.[1]

Conclusions.

The results of the experiments described show that solid carbon dioxide may have a certain practical value in dealing with burning liquids, but that its usefulness depends on the character of the liquid and upon the appropriate method of application being employed. In general, the means by which the solid CO_2 can be effective depends on the size grading of the material used. The more finely divided grades float on the liquid surface and absorb heat from it, but the coarser grades sink and cause a stirring action. The limiting size between floating and sinking differs for different liquids, but the determining factors have not been elucidated.

Solid CO_2 can obviously cool the surface to lower temperatures than water can. There is therefore a range of liquids (of flash point around atmospheric temperature) which are susceptible to extinction by a surface application of CO_2 powder but not by water spray. It is with such liquids

that solid CO_2 might be of some practical value. With liquids of very high volatility (low flash point) the requisite surface temperature for extinction is well below atmospheric and can be attained only by a very liberal application of solid CO_2.

With increasing flash point of the liquid, the surface temperature during burning is increased, and the surface application of solid CO_2 becomes increasingly effective so long as the liquid is not one of the type that forms a hot zone during burning. In this latter case very much larger applications become necessary, because not only must the temperature of the surface layer be lowered but the whole hot zone must also be cooled before extinction can occur. The necessary application of floating solid would therefore increase continually according to the period of previous burning (*i.e.*, the depth of hot zone).

With liquids whose flash point is definitely above atmospheric temperature, however, extinction by stirring becomes possible, and then it appears that a given weight of solid CO_2 is most effective if applied in lumps of such a size as to sink and cause stirring action. The value of this method relative to the method of surface application appears to increase with increasing flash point of the liquid, and is particularly great in those cases where a high-temperature hot zone is formed.

The use of submerged CO_2 is subject to the usual limitations of gas stirring. Thus, it is ineffective if more than a certain proportion of the oil has been assimilated into the hot zone and in any case, except on the smallest scales or with prolonged application, it leads only to the surface clearance of flames and leaves an edge-fire requiring auxiliary means for its extinction. It should be noted, however, that the surface application of CO_2 powder at this stage provides one such auxiliary means.

The edge-fire is maintained primarily by the heat content of the vessel walls. The latter is always a matter of concern in the extinction of fire in burning liquids and has a marked influence on the requirement of surface-applied CO_2 for extinction. Thus, if burning is allowed to continue for some time before the CO_2 is applied, the application required will be much increased owing to the necessity for cooling the vessel walls as well as the liquid.

From a theoretical standpoint the experiments on extinction with solid CO_2 are interesting because some of them provide an instance of extinction by pure cooling effect at the liquid surface. It has been shown that the CO_2 gas evolved is not in sufficient quantities to have any appreciable flame-suppressing effect. The CO_2 is not very soluble in the burning liquid, and is therefore without any important effect on the volatility thereof except by virtue of its cooling action. The fact that the effect of certain factors, such as the flash point of the liquid, the existence or otherwise of a hot zone, and the difference between the use of the solid in the floating or submerged condition, can be explained in the terms of the preceding paragraphs, provides evidence that the views regarding the mechanism of the burning and extinction of liquids, previously developed and outlined in the introduction to the present paper, are essentially correct.

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Reference.

[1] J. H. Burgoyne and L. L. Katan. *J. Inst. Petrol.*, 1947, **33**, 158.

DISCUSSION.

R. K. TARRANT: Can you tell us what is the difference, if any, between extinction temperature and flash point?

DR BURGOYNE: There is a difference. I think the extinction temperature is more nearly related to what is known as the "fire point," *i.e.*, the temperature for stable burning, as distinct from flashing; it is somewhat higher than the flash point.

FRANCIS STEAD: One of the problems we are up against in industry is that presented by linseed oil as used in printers' ink and litho ink, at a temperature of 140° F. If the temperature is slightly higher there is a boil-over and a chemical reaction which raises the temperature to about 800° or 850°. The fire is difficult to extinguish. Do you know whether the application of solid CO_2 is a possible way of handling that fire?

DR BURGOYNE: It is a rather different problem. The trouble is due to an exothermic chemical reaction taking place throughout the whole body of the liquid, from the bottom of the tank right up to the top, and an immense amount of heat is being evolved in consequence. I cannot think of any way of assimilating that amount of heat, and I do not see that solid CO_2 would help.

G. A. V. WEST: You have made the point all through your paper that the fires were extinguished by cooling; yet you were using CO_2. In the course of your experiments, did you take into your calculations the possibility that the fires were extinguished by a certain amount of blanketing, plus cooling?

DR BURGOYNE: Yes, we did look into that point. We carried out comparative experiments in which we bubbled gaseous CO_2 through the liquid from a number of points, and we found that the effect was negligible as compared with the effect of the use of solid CO_2 giving off gas at the same rate. So that I think it is clear that blanketing had very little to do with it.

J. E. FARRELL: When you used large pieces of solidified CO_2 which sank into the oil and produced a stirring effect, did that leave an edge-fire which had to be extinguished by auxiliary means?

DR BURGOYNE : Whenever you use a gas-stirring technique you do leave an edge-fire. It is a very small affair, and it can be put out by various means; one means appropriate to this particular case is to scatter a little powdered CO_2 on to it, and that will do the trick.

J. H. HUTCHINSON : It may be interesting to the meeting to hear something of our experiments at Billingham with some water-miscible fluids. We were interested in putting out fires of acetone and methanol, and we experimented with water and foam on fires in a tank measuring 10 ft $\times$ 3 ft. We were unable to extinguish fires by the use of water in various forms, but during the experiments we did incidentally succeed in putting out fire by steam flash-off from the hot surface of the tank side. The fire went out not by cooling, but by being smothered with the flash steam. With foam, however, we had complete success with both chemical and mechanical foam, though at a higher rate of application than one would normally expect to use on a hydrocarbon fire.

It appears from Dr Burgoyne's remarks that the application of solid CO_2 would be preferred to the use of foam, and I would like to have the point cleared up. Does he think that, for dealing with fires of these solvents, the use of solid CO_2 is superior to the use of foam, to which latter we certainly gave preference?

DR BURGOYNE : It is rather difficult to make a comparison. I believe that foam is rather ineffective on the water-miscible solvents, as compared with its use on hydrocarbons; but I have no great experience of it. Nevertheless, as you say, it does work; but does it involve the adoption of rather high rates of application per sq. ft. of area?

J. H. HUTCHINSON : Our rates of application, which were a shot in the dark, were about five times as great as one would normally use on a hydrocarbon fire; *i.e.*, we used about 5 gal/sq. ft. of burning surface per minute. Our experiments, however, did satisfy us on this point, we were unable to extinguish fires with water, but we were quite successful with foam.

I was interested in Dr Burgoyne's remarks about CO_2, because it has always been found to be of help in putting out fires. However, in view of the fact that we were able to smother the fires fairly quickly with foam, I would like to know whether CO_2 is to be preferred to foam for the purpose mentioned.

DR BURGOYNE : I do not think we wish to try to say that one thing is better than another; it is rather a case of suggesting to you that solid CO_2 is quite an effective method, and that you might like to compare it with the use of foam in practice.

With regard to smothering, you can deal with these low flash-point liquid hydrocarbons by using some inert gas such as CO_2 or steam, or possibly water fog. But, in order to use those methods effectively, you must attain complete cover; otherwise you have trouble with flashback.

D. A. HOUGH : The authors were asked about the effectiveness of CO_2 from the blanketing point of view, and Dr Burgoyne led us to belive that it was not very effective. On my television screen recently, however,

I saw a petrol blaze which was extinguished in about 3 secs by blowing CO_2 on to it from a nozzle. The quantity was only a barrel of petrol; but I should be interested to know whether that treatment was effective because the fire was a small one, or whether the same method could be used on a larger scale.

DR BURGOYNE: I think I have been misunderstood a little on this matter. What I have tried to demonstrate is that the blanketing effect of CO_2 was not important in our experiments, where the effect was obtained by the cooling action of solid CO_2. In my last reply I said that one could proceed by the alternative method of blanketing with inert gas, which is entirely effective if there is complete cover. It becomes increasingly difficult to get complete cover, as unless a fixed installation is employed the burning area increases.

F. P. MILLS: Supposing a diesel-oil vehicle took fire in the Mersey Tunnel and the burning oil ran all over the place. What means would the authors consider best for extinguishing such a fire? Would they recommend fog nozzles, foam, or CO_2?

DR BURGOYNE: I think this is rather a tricky question! Without trying to give an authoritative reply, I should be rather inclined to suggest the use of foam. I think there is quite a lot to be said for the other methods, but the use of foam is obviously a very convenient means where you have burning liquid running all over the place.

A. P. L. SULLIVAN: Can solid CO_2 conveniently be conveyed to the place where it is to used? Is its use practicable from that point of view?

DR BURGOYNE: Solid CO_2 is becoming a great deal more familiar to us than it was formerly, and in many chemical works it is readily available; I am sure that I.C.I. have plenty of it. I think it is rather a case of considering its application in those places where there is plenty of it about.

A SPEAKER: As a point of interest perhaps I may recall an experience in Burma in the year 1913, when a 250,000-gal tank of kerosine caught fire. We had a CO_2 refrigerating plant, and there was a 2-in connexion near the surface of the liquid in the tank. We had CO_2 in bottles under high pressure, and we connected the ends of those bottles and used the contents on the fire. I do not guarantee that the CO_2 actually put out the fire, but the fire was put out, and I think the CO_2 helped to blanket it. That was before the days of foam, of course.

A SPEAKER: How is solid CO_2 applied, for I imagine that you cannot get near enough to throw it on to a big fire? Did the authors throw it on?

DR BURGOYNE: Yes.

FRANCIS STEAD: With regard to the television demonstration that has been mentioned, and with which I was connected, we do use CO_2, though not wholly as a gas; when discharged from the extinguisher, some of it

comes out as solid CO_2, in very small particles, and that is how we get the desirable effect.

DR BURGOYNE: I suggest that you should consider whether it is not worth your while to aim to produce solid in the discharge from CO_2 extinguishers.

DR R. C. FISHER: I have the impression the authors stress that in connexion with fire extinguishing by means of CO_2, cooling represents the most important feature in the extinguishing process. If this was the case, there seems to be little point in using solid CO_2, because the latent heat and sensible heat of this material are much smaller than the corresponding characteristics of water.

DR BURGOYNE: That is true; if the extinction temperature is such that water can be applied, I do not think anyone should use anything but water to achieve cooling, for the reason you mention. My point is that CO_2 extends the range. You could not use water for extinguishing liquids flashing below about 40° C, but CO_2 extends the range to liquids flashing considerably below 0° C.

E. THORNTON: We are overlooking the fact that what keeps a fire going is radiated heat, and that you cannot effect cooling unless you get rid of what is causing the heating. The fact of being below atmospheric temperature does not matter seriously if you have foam over it. The heat must be disposed of by evaporation.

We are in danger of again overlooking what is the main cause of extinction, *i.e.*, alternative duty for the radiant heat other than supplying oil vapour. Merely putting on a limited quantity of CO_2 at low temperature would not bring and *keep* the oil surface at that temperature. That can be achieved only by having sufficient heat-absorbing or cooling capacity present to deal with the radiant heat adequately. This done, as Dr Burgoyne says, the temperature reduction possible is greater with cold CO_2 than with water, and extends the range of cooling by circulation to substances for which air would be useless.

DR BURGOYNE: I agree.

The following paper was then read:

SOME PRACTICAL ASPECTS OF THE PROBLEM OF APPLYING FOAM TO LARGE TANKS.

By E. THORNTON (Fellow).

SUMMARY.

1. Very large tanks require inordinate amounts of foam and very much complicate the problem of overhead application, requiring many fittings and much pipe work along conventional lines and large tenders if mobility of generator is sought with minimum pipe work. Larger and lighter pipes and limited points of entry seem worth consideration.

2. Base injection is attractive on account of lower quantity of foam required and greater certainty of entry; the possibility of eliminating all extra pipe work becomes possible and practicable as foam-making plant can work against higher back pressures.

3. "Portables" should have means of elevating plain pourers only—foam being generated at ground level and outside the bund.

4. It is suggested that the oil industry, collaborating with such other interested parties as are willing, *e.g.*, insurance companies, Government research and service departments, should stage large-scale tests in a suitable place to put this matter on an adequate technical foundation to enable the very attractive solution suggested either to rest on firm foundations or be dismissed from our minds; in any case to put it beyond the reach of futile arguments without adequate facts.

INTRODUCTION.

THERE is now little question that during the early stages foam in adequate quantities will extinguish fires in tanks or reservoirs of oil or petrol, and there are several types of foam commercially available for the purpose. In the case of very large tanks, *i.e.*, over 80 ft in diameter, technical difficulties arise, namely in getting foam on to the fire at an early stage and at an adequate rate. This paper presents a discussion of these difficulties, some solutions that have been found, and tries to assess the trend of future developments.

ESTABLISHED FACTS.

Considerable experimental work on the small scale, not quite so much on the large scale, and a good many experiences of actual fires, all lead to the conclusion that if a cover of foam can be established, then practically any oil fire can be extinguished. It is now known that the principal effect of this foam cover is to nullify the effects of the radiant heat from the flames or hot metal above the oil, and thus prevent the vaporization of fresh oil necessary to maintain the fire. This is equally true whether foam is applied from above or below the oil surface. In the case of fuel oil, or hot-zone-forming oils as they are now called, the effects of previous burnings have to be counteracted at the same time as the supply of new radiated heat is being dealt with, which dual duty affects the rate of application necessary, and unfortunately introduces certain new hazards such as "foaming" or "frothing over" as a consequence of the rapid generation

of steam. The method of application decides what other effects tending to destroy the foam are permitted to operate, particularly on fires which have been going for some time. Thus a long-delayed passage as "flock" through hot flames and gas will obviously lead to destruction of much foam before the surface is reached, and a long passage through petrol will also tend to destroy some of the foam without useful effect. In the case of heavy oils, it has been shown in previous papers that stirring, however induced, which brings cold oil to the surface in adequate quantities, helps by cooling to limit the supply of vapour and, in favourable circumstances, can prevent it altogether and extinguish a fire on the relatively small scale of 9 ft diameter.

The papers by Burgoyne, Katan, and Richardson show that foam injected at the base can combine both effects, *i.e.*, cool by both circulated cold oil and by the supply of water as foam, and may require less foam than either the air alone, or the water alone, which go to make the foam. This is on a very small scale, and is not yet proved on the large scale. The amount of radiated heat to be dealt with per square foot seems to increase with the diameter of the tank, and it would be unsafe to infer from the measured quantities of foam base-injected in the small tank, that proportionate quantities would extinguish fires in a very large reservoir of oil such as a 100- or 140-ft-diameter tank. There is less certainty about petrol to date, for the reason that circulation is not necessarily an advantage, since it is improbable that petrol will ever be circulated at such a high rate that no vapours can be produced, and also that it may not be easy to obtain complete cover from below in the case of very large tanks. There is less doubt about the efficiency of foam applied from above or to the surface of burning petrol.

Practical Difficulties.

Foam Making.

Prior to the war, foam was almost entirely a chemical affair, particularly in America, made either from twin solutions, twin powders, or single powders, and there was no serious difficulty about supplying at any given rate from fixed places of supply. The difficulties increased when mobility was required, largely on account of the large quantity of powder to be handled or the large quantity of solution to be carried. The practical limits for powders were considered to be somewhere about the 70-ft tank size, no limits being admitted for twin solutions up to 120-ft diameter tanks. In Europe and Britain a different kind of foam was established, produced with air as the gas component and water containing a suitable foaming agent as the liquid component, and during the war this type of foam was adopted for N.F.S. use in the form of Pyrene air-foam, in which the foaming agent and water were separately induced by the water stream, whereas the Air Ministry tended to favour the type of foam-maker which passes the air and the compound containing water through a pump together, the pump providing the agitation necessary to produce foam. Both these methods are well established and commercially available. Generally speaking, it may be said that the methods using pumps through which everything passes, take more power to produce a given amount of foam, but have the advantage that the foam so produced can be forced through any reasonable

length of pipes, and that control is maintained over the desired expansion or the ratio of air and liquid independently of the need to deliver the foam through the pipe-work system.

A third method, not to my knowledge commercially available, produces air by means of a compressor, or even by the gases from an explosive such as cordite and forces the necessary liquid and gas through gauzes to give the necessary mixing which produces foam. This method also has the advantage that the proportion of air to liquid can be varied at will, and is independant of the pressure necessary to get the foam through the system. In this case again, the power requirement for pumped air is considerable, the methods of inducing air and compound by the pressure of the water being favoured generally because of simplicity and the fact that pumps would be required in any case for water streams and could be used to provide foam by the addition of a branch pipe only. The earliest forms of so-called foam-making branch pipes were satisfactory for throwing a jet of foam, but were unable to force the foam so made against resistance amounting to more than a few feet head of water pressure. Successive modifications have overcome this limitation to the extent that generators are now available which will continue to function when working against a back pressure of 30 p.s.i. or more, but under these conditions a smaller amount of air is induced, and the foam consequently has a lower expansion. It is not the purpose of this discussion to consider the merits of high expansion or low expansion, or of viscous or fluid foams, as they constitute a separate issue from the one under discussion. Suffice it to say that several methods are commercially available of producing foams capable of extinguishing oil fires, and producing it in quantity in a manner which will enable it to travel through considerable lengths of piping.

Foam Application.

Overhead.

There are two main methods of entry in use for overhead application, *e.g.*, over the roof or through the side just below the roof. Mixer boxes delivering over the roof are provided for twin solutions and plain pipes for foam already made, whilst special entry boxes with seal are used for air foams.

The problem of sealing against condensation of light vapours is not difficult, and provided the tank remains intact there is not much to choose between these various methods—perhaps side-entry with suitable arrangements to prevent loss of capacity is slightly better on the whole than entry through the roof. Any such connexions, however, are liable to be disrupted by explosion or by distortion effects, particularly with wholly welded tanks, and thus a doubt is always present as to whether such fittings will be operative when needed. The provision of three or four entry points to a tank obviously gives more chance of one or other point being left intact, but involves very much extra pipe-work, and since no one point of entry is likely to take the full quantity required, the arrangement is still not entirely reliable. Methods of ensuring smooth flow on to the surface suffer from the same objections, *i.e.*, that they might be disrupted by explosion, and have the further disadvantage that they necessitate still further fittings

inside a tank, an arrangement which nobody really likes if it can be avoided, owing to difficulties when cleaning.

Base Injection.

Base injection through the tank product lines offers the most attractive solution of this problem if only it were proved for large-size tanks. Even on the largest scale it is probable that the total quantity of foam required, or at least the total rate of application, will be less than overhead requirements owing to the stirring effect, though these stirring effects are as yet untested on the larger scale. The remaining question then turns on the hydraulics of getting foam through pipes of considerable length, but will be dealt with under the next heading.

"Generator to Tank" Problems.

Having decided on the method of delivery for foam into the tank, and the particular type of foam which is favoured, an important question is then, "Where should the generator be fixed and how many are needed?" When considering quantities of foam required and rate of application, it was at one time the practice of N.F.B.A. to stipulate the quantity and the rate which would be necessary for the largest tank in an installation, but in view of the considerations dealt with in the previous paragraphs, there remains the question of the location, if fixed, or the type of appliance to be used. It is here that the attractiveness of base injection, if proved workable, is greatest of all. Every tank farm, of necessity, has pump-houses and product lines connected to groups of tanks, and any method which can make use of these has obvious advantages over any alternative system which has to have a still further network of pipes and fittings solely for fire purposes. A solution to the problem which involved the installation of one major generator of foam at the product pump-house, with quickly made connexions to the product lines when required and necessitated no further man-power than the pumpsman who had to start it, would be something like an ideal and demands careful consideration. What stands in the way of such a solution immediately?

Effects of Foam Passing Through Long Lines.

A limited amount of experience would indicate that once made, a foam is likely to improve, rather than be impaired in efficiency, by passing through long pipes, and as the capacity of 700–800 ft of 10-in line is negligible in relation to the rate at which foam is required, neither delay nor loss of foam are serious when this method is used.

Effects on the Generator.

These effects are more serious, but not sufficient to rule out such a system. Product lines are always of adequate diameter and usually capable of passing 50,000 or 60,000 g.p.h. of oil to the pump under relatively small pressure of 10 to 20 p.s.i. In most cases the friction pressure drop when passing the necessary quantity of foam through would be within the design capacity of modern foam-making equipment. It would be unsafe at this stage to infer from this work carried out on the 22-in diameter scale that

such small relative rates of application (*i.e.*, foam gal per sq. ft. of surface). would be successful on large tanks, and it would be considerably safer, pending suitable experimental work, to assume that at least 5 gal foam per sq. ft. of surface would be required. This means 5000 g.p.m. for 116-ft-diameter tanks and over 7000 g.p.m. for 140-ft-diameter tanks. No figures are available at the moment for assessing the resistance of foam passing through pipes of more than 6-in diameter, but it seems reasonable to assume that the pressure required would be the order of 6 p.s.i. only for getting the foam through the pipes. In the question of base injection, however, a further pressure of 20 p.s.i. or so must be added to overcome the static head of the oil in a modern tank of 55 ft height, this being by far the greater proportion of the total pressure to be overcome. It seems clear, however, that at least 30 p.s.i. may be considered practicable at the generator. As this is usually within the capacity of the pump type of foam-makers and also within the capacity of the latest type of pressure generator, using induced air, there is certainly a strong case for fixing the foam-making appliances at the pump-house and utilizing quickly made connexions to any particular tank which happened to be on fire.

The validity of this very attractive scheme, however, turns on the degree of certainty that can be placed in base injection as a method of handling large fires in tanks, and it should not be beyond the powers of co-operation of the oil industry as represented by the A.P.I., N.F.P.A. in America, and the Institute of Petroleum and the various insurance companies to stage suitable experimental work, preferably in some remote area where the hazards would not matter, and where the oil would carry no transport costs, to settle such an important issue for all concerned.

The problem of which generator to use in a scheme of this kind has to be viewed in the light of this back-pressure requirement when delivering prepared foam. In schemes using twin solutions, twin powders, or air foam with the generator on the tank, the problem is simply one of hydraulics or liquids and has no difficulties. When it is proposed, however, to pass foam, rather than foam-making solutions, through the whole length of the line after making, the problem will be a little different. Twin solutions, or twin powders, with the mixer in the pump-house should, as stated, present little or no difficulty, and this applies also to mechanical foam generators which pass everything through the pump, and send out the foam in a positive manner. The inducing type of foam branch pipe, however, presents more difficulty, and as stated, recent improvements of design have overcome at least one difficulty of keeping the generator at work against a reasonable back pressure. Under these conditions, however, the generators make a foam of considerably lower expansion and consequently the stirring effect of such foam would be lower, although, of course, provided the foam is stable, the water-carrying effect is higher. This is probably a question of design, since the smaller or so-called No. 10 Generator at present on the market suffers less in this respect than the larger No. 20, and if the demand is there makers will almost certainly rise to the occasion and supply. At present, however, these facts have to be borne in mind when deciding which generator to use if it is desired to plan bottom injection with the foam travelling from the pump-house through the product lines. A further feature of this type of generator is that it works with increased

efficiency when the inlet-water pressure is higher, and under these conditions working the generator at the pump-house is a simpler proposition, since it avoids the necessity of long lines carrying high-pressure water or of the hose being liable to burst or part from its couplings at the higher pressures. So much then for the very attractive, but as yet imperfectly tested, base injection for large oil tanks.

Overhead Application.

The friction loss in passing foam through small pipes, *i.e.*, 6 in and less, is a serious factor for fixed installations with long runs of pipe-work, for all but the pump type of air foams including twin-solution foams and twin-powder foams. During the war it was found that 400 ft of 4-in pipe was too much for the standard No. 25 single-powder generator (from stock) using water at 100 p.s.i. and delivering 1400 to 1600 gal of foam per min, and recourse was made to a complicated arrangement of twinned and quadrupled hose to get over the difficulty. 6-in pipe-work gives more flexibility if separate inlets, three or four to a tank, are considered, but obviously takes a lot of steel and festoons the place with pipes wherever the system of three or more separate inlets to a tank is adopted. On the other hand, if a fixed point with short lines is preferred, then mobility is obviously limited when quantities like 800 to 1000 lb/min of powder are required for each tank and have to be transported and handled at the time of the fire. The difficulties are so great that the idea can be abandoned when thinking in terms of 140-ft-diameter tanks. By arranging a central generating house or houses to cover tanks within a radius of 400 ft and serving the generator for powder from a specially designed powder bin with special outlet valves or using pressure-type air foam, the pipe-work problem can be simplified by using 6-in flexible hose from the central point to link up when required with the 6-in pipe-work carried to 40 or 50 ft, say, from the tank, but it is still a fairly complicated lay-out. If roads are convenient, a further simplification can be made by running 6-in pipe-work from the tanks to a convenient roadside point, and having water available along the roadside, so that air-foam tenders can be used to deliver foam to the 6-in pipe-work. This requires very large tenders, and in the case of 140-ft-diameter tanks with a requirement of 1500 gal of water per min at 200 p.s.i., several will be required.

The advantages of centralization which are possible with the base-injection scheme are also obtainable for overhead application by laying suitable mains from the pump-house with branches to the separate tanks at a distance at least 50 ft away from the tanks, normally closed valves being opened as required to the particular tank on fire at the moment. Such pipe-work could be very light, similar to gas mains, and the scheme is not by any means impracticable or unduly expensive, provided we cease thinking in terms of oil pipes for everything at an oil installation ! Even single-point entry is obviously possible, and the nearest equivalent to base injection, but there is the ever-present doubt as to whether the fittings will be there after any explosion has distorted the tank.

Portable Foam Devices.

However elaborate our plans have been, the possibility that a tank may be on fire and all the planned points of entry out of action, can never be

entirely ruled out, though this is least likely in the case of base injection through product lines. When this occurs, getting foam into the tank is always a hazardous and frequently impossible business, owing to the unpredictability of where holes will be left in the roof or between the side and the roof, and the difficulty of close approach to a large tank with its terrific radiant heat, coupled with the difficulty of elevating whatever device is to be used for getting foam into the tank. Throwing foam into a tank from a jet has been done on occasions, but is not an attractive proposition. The problem of elevating men or material to a considerable height is one with which the fire service is very familiar, and makers of equipment have no difficulty in providing extending ladders for this purpose. The standard turntable is often quite impractical on a tank farm with its rough ground and bund walls to be scaled, and much lighter equipment has to be found. With the new type high-pressure air-foam generators it would seem most attractive to provide a light extension ladder to carry up a pourer head or nozzle which was connected by a length of 50 ft or so of 6-in flexible hose to the generator base, the generator to be supplied with compounded water from pump or tender located outside the bund wall. The carrying of twin solutions, twin powders or similar powders for a job of this size is complicated, and the only workable alternative would be one of the pump types of mechanical foam-makers or tenders, though this would need to be of very much larger capacity than any used at present. It is possible in an emergency, and has been done, to burn holes through the tank side when the oil is low, a condition which usually gives most distortion of the tank, but it is very unlikely that any serious damage will have been caused to a tank without leaving an opening in the roof through which foam can be poured, and it is more practical to elevate the pourer to an adequate height and pour from there, leaving the foam to find its own way to the oil, as such a method would cool the roof plates at the same time, providing sufficient foam was available.

Discussion.

F. P. Mills : Mr Thornton has warned us against falling into a trap, and he has used the phrase " reliable foam." I would like to ask what is a reliable foam ? Is it a chemical foam or an air foam ?

Mr Thornton : Any foam, " for the purpose of the act," is reliable if it puts the fire out ! We have considerable evidence that the stability, as normally measured, is not so important a factor as we had thought ; I have evidence, which I am sorry I cannot produce at the moment. But I made an oven very similar to the one mentioned in Dr Clark's paper during the war. It stood on and was surrounded by insulating brick ; an electrical heating element was placed on top and a dish containing water put into the oven thus formed. Weigh the dish and its water, give it a minute of exposure, and then weigh again and take temperatures. When the element puts 300 B.Th.U/sq.ft./min. into the dish, I say that it represents a flame. You can use foam, no matter of what quality—chemical or air foam. The amount of water evaporated corresponds to the amount of heat put in.

A reliable foam is one which is so stable that, when it is put on top of burning oil, it is permanent in the sense that it remains there to protect the

oil until it (the foam) is all evaporated, as distinct from a foam which simply breaks down to liquid and runs away through the oil.

Such stability, however, does not prevent or lessen evaporation, and this fact accounts for the correlation between amounts of foam required and intensity of radiation, which is often observed and which warrants such preoccupation with water content of foams.

There are many foams available, and the manufacturers all make claims for their own products.

R. G. AIRD : A lot has been said with regard to the application of foam to tanks of burning oil, and I would ask for clarification of a point which has not been mentioned so far this evening. I have always been given to understand that heat, to a certain extent, tends to break up a foam. Is there any recommended point for the application of the foam ? I believe an experiment was carried out some time ago in which a hole was bored in the side of an oil-tank and foam was injected directly to the surface of the oil. Can you say at which point foam can be most beneficially applied ?

MR THORNTON : It is most beneficial to apply foam at the surface of the oil; but the problem of getting it there is not so easy to solve. It is a matter of compromise, therefore. If the literature of the fire authorities in the United States up to, say, 1938, is read many fancy ways of doing it will be found—" elephants' trunks " of asbestos, little gadgets around the tanks, and so on—all good in theory.

In my view there should be a thick stream of foam, fed through a pipe and pouring through the side of the tank somewhere near the top, falling in a thick stream inside.

During the war the Petroleum Board adopted a scheme which involved a small diverting baffle inside the tank which was supposed to direct the stream generally down the tank side. A trial I made showed that a snow-storm of flaked foam was produced instead, and this, by reason of exposure of more surface, in my view was more likely to be destroyed by hot gases than a hefty stream.

There can be an *ad hoc* solution in particular cases; but the proper place of application of foam is on the surface of the oil. It can be injected down below if base injection is fancied and the fence as to whether or not it works on a large scale is jumped, but it gets to the surface before it works anyway.

DR RICHARDSON : I like very much the idea of pumping the foam through the product lines, but I am inclined to think that a foam which is oil-resistant will have to be used, for there is a layer of oil clinging around the walls inside the product lines. It is a matter of experience, as I have found during experiments, that whenever foam comes into contact with oil it breaks down into a mixture of water and air. Alternatively, a way might be found of removing the layer of oil which clings around the inside of the walls of the product lines ! Otherwise, if foam is pumped a distance of 700 or 800 ft through product lines there will be just a mixture of water and air at the end. If this is applied to the bottom of a tank, the water will remain at the bottom and the air will rise up; if it is applied at the top of the tank, the air will go to waste and the water will pass through the oil to the bottom before it has time to cool the oil.

MR THORNTON : Were you using pipes of $\frac{1}{2}$- or $\frac{3}{4}$-in dia ?

DR RICHARDSON : Yes.

MR THORNTON : I am talking of pipes of about 10-in dia. If foam is passed through such pipes there will be a little deposit on the sides, but the great majority of the foam will go through and into the tank. It is a scale effect.

MR BALDWIN : It has been indicated that if the rate of application of foam is low, it is better to put it into the tank at the bottom, but if the rate is high it is better to apply the foam at the top. If pipes are connected to the top of a tank in order to introduce foam in large quantities, will there not be a valve which is always closed, so that a man has to get right at the tank in order to open the valve or valves in the event of a fire ? I do not know whether that difficulty can be overcome. On the other hand, if bottom connexions are fitted to the tank for the introduction of foam, will the line always be open right back to the point at which the foam is made ?

MR THORNTON : Probably it would be preferable to fit non-return valves rather than those which have to be opened and shut manually. It will be a matter of fighting it out between the fire department and the oil staff.

An alternative method of top application is by making use of the product lines. By connecting the product line also to the base of the tank through a non-return valve, the product line can be used for base injection.

There is an experiment mentioned in the first paper presented this evening, where foam was applied at a high rate, extinction being effected in $2\frac{3}{4}$ min. The authors put forward a diagram giving the ratios of burning time to extinction time. The practical issue is that there would seldom be quantities of foam such as were used in that experiment. For large tanks we should be thinking of 50,000 g.p.m., and I do not think we should contemplate applying foam at such rates to large tanks.

MR BALDWIN : I am doubtful about the non-return valve. Surely it has to be non-return in two ways !

MR THORNTON : No. You are pumping either oil or foam through the pipe, and a non-return valve will open, whether you are pumping oil or foam into the tank, but it will not allow anything to come out. It is merely that in case of fire you pump in foam instead of oil.

T. A. VARLEY : There is a point in connexion with pipelines which interests us as firemen.

In a tank farm do separate pipelines run direct from the pump-house to the individual tanks, and are we to understand that it is the normal practice to keep these product lines full from the pump-house to the tanks ?

Some reference was made earlier to there being an isolation valve attached and alongside each tank, and if so are we to understand that these valves are kept closed and thus the pipelines from the pump-house to those valves are kept empty ?

MR THORNTON : I should say they are always full. Unless someone in the institute contradicts that, I will presume that it is so.

MR THOMPSON : In the light of present knowledge, would you care to recommend " up to the minute " methods for dealing with a fire in, say, a 60-ft tank containing fuel oil, *i.e.*, oil which forms a hot zone and which has been burning for several hours.

MR THORNTON : You have chosen a very awkward but unfortunately possible case.

The first thing is to cool externally as much as possible by water—avoiding entry of water into the tank.

If surface or overhead application is chosen, then caution should be used at first to control frothing; watching and being prepared to stop if frothing gets out of hand.

Once the " legacy " of hot oil is cooled and only current radiant heat has to be countered, then $\frac{3}{4}$ gal/sq.ft/hr. or over should finish the job.

If base injection is contemplated, then even more care is required, and I should recommend starting application *without* compound ! This would in effect give air circulation only without undue risk of frothing by water when flames began to recede; then using compound for standard-case injection should have a good chance if in adequate quantity.

S. HART : Is there any technical reason why the petroleum people use pipes of so small a size, and why they could not fit product pipes large enough to convey sufficient foam, when necessary, to be able to deal with fires efficiently ?

MR THORNTON : I do not know about technical reasons, but probably £ *s. d.* has something to do with it in Britain. Further, nobody likes a lot of pipes around tanks, and not many people like fire engineers if they can do without them ! People will say they do not wish to smother things with fire-protection devices, but they will insure against fire. When I was discussing a certain problem with one gentleman he asked me how much the company had lost during the previous year as the result of fires. In a well-regulated company, operating in an equable climate, the answer is usually very little indeed.

In putting forward any scheme, it is more difficult to obtain sanction for a 6-in pipe than for a 3-in pipe. Previously we have not considered the very large quantities of foam that we have been discussing to-day; but if a pipe has not to be of great length, then it need not be of large diameter. However, the expense could be lessened if we ceased thinking in terms of fuel-oil piping for what ought to be gas-carrying lines and much more use could be made of very light pipe work.

A SPEAKER : Do you experience many tank fires ? If you do not, how do you assess the extent of the fire hazard ? What are the hazards ?

MR THORNTON : The answer to the first part of the question is " No." The second part has been the subject of innumerable inquisitions. The storage of petrol in tanks with floating roofs is almost foolproof; when not

under floating roofs, petrol can constitute a hazard every time. Ten tons of petrol may be distributed in the form of vapour every time a 10,000-ton tank having a fixed roof is filled with petrol. One method used is to stand a tank in a " saucer," so that the contents, if they escape, are isolated from other tanks. If there are such secluded spots, a labourer might decide to have a smoke, and might cause a fire. It has been alleged that a spark caused by a manhole door falling has caused a fire.

Normally, at any rate in Britain, there should not be many fires, and we do not experience many, relative to the amount of oil handled and the number of tanks used. Abroad there are factors such as lightning and the overheating of black tanks (before aluminium paint was used). There are some oils which give rise to a corrosion layer of ferrous sulphide, which, when flaked off by a man walking over a tank, may oxidize and cause a hot spot capable of giving rise to a fire, in favourable circumstances.

A SPEAKER : A heavy fuel oil, I understand, would not give off vapour ?

MR THORNTON : No. I have been speaking about petrol. A fuel-oil tank should never go on fire—but it does not seem to know that yet !

Vote of Thanks.

J. E. FARRELL : I feel very privileged indeed, seeing that we of the Institution of Fire Engineers are visitors here, to have been asked to propose a vote of thanks on behalf of the gathering.

Many of those present this evening also attended the meeting that was held here three years ago, and the interest displayed on that occasion was very similar to that shown this evening. I hope we will have other discussions, when further information on this subject is available.

The amount of work devoted to experiments which are discussed in papers is not often reflected in the comparatively short discussions which follow, having regard to the time available; and the authors have also compressed a lot of information in order to bring out the salient points. We are very much indebted to the gentlemen who have prepared the papers and to those who have assisted them in this work; and among those who have been connected with the work I include Viscount Falmouth.

We on the fire-fighting side have been particularly interested. At one stage, I think, every fireman in the country felt that it was dangerous to go anywhere near an oil-tank when it was burning, in case there was a slop-over or a boil-over. Then we passed to another stage; and we feel that there is still room for further investigation.

It is a great pleasure for me to express thanks to the President of the Institute of Petroleum and his colleagues, and to the gentlemen who have prepared the excellent papers presented to us.

A. T. WILFORD : I have much pleasure, on behalf of the Institute of Petroleum, in seconding the vote of thanks to the authors of the papers. We must congratulate them on the very able way in which they have presented their papers, and also on the even more able manner in which they have handled one of the most quick-fire discussions I have ever had the pleasure of hearing. I thank them most heartily on behalf of us all.

(The vote of thanks was accorded with acclamation.)

A. H. NISBET (President of the Institution of Fire Engineers) : I would like to take this opportunity of expressing to the Institute of Petroleum the very sincere thanks of the Council and Members of the Institution of Fire Engineers for having given us the privilege of joining with you in listening to such excellent papers and also for the pleasure of taking part in most interesting discussions.

In asking me to act as chairman, you have conferred an honour greatly appreciated by the Council of the Institution of Fire Engineers. We are all looking forward to further meetings of this nature.

May I be permitted to add my personal thanks and assure you that it was a real pleasure to travel from Scotland to attend this meeting.

E. A. EVANS (President of the Institute of Petroleum) : I can assure you, Mr President and members of the Institution of Fire Engineers, that the Institute of Petroleum is more than proud to have had such a wonderful evening. As has been said, we have had an extraordinarily rapid succession of questions and answers, perhaps the most rapid I have ever heard : I thank you all very much indeed; we have enjoyed very much having you with us, and we hope that this will not be the last such occasion.

(The meeting then closed.)

OIL FROM OIL SHALE—EXPERIENCE IN THE UNITED STATES.*

By R. A. Cattell.†

Abstract.

The Bureau of Mines of the U.S. Department of the Interior is conducting an oil-shale research and demonstration-plant programme. Other Government agencies, industry, and educational institutions are co-operating. Studies indicate that 100,000 million brl of oil may be recovered from shale in the best 1000 square miles of the Green River formation in Colorado, and much oil will be available from an additional 15,500 square miles of that formation in Colorado, Utah, and Wyoming.

A highly mechanized system of underground quarrying has been developed to mine shale for 60 cents a ton. Research is developing fundamental information concerning the characteristics of oil shale and shale oil. Tests with several types of retorts are being conducted at the demonstration plant near Rifle, Colorado, and at privately owned plants.

Low-boiling shale-oil distillates have a hydrocarbon composition similar to cracked petroleum products, but include substances that are characteristic of coal tars. Hydrogenation will improve these distillates so they can be refined by conventional means to produce satisfactory substitutes for petroleum products.

Estimates indicate that shale oil can be produced with continuous retorts at costs below $2.00 a barrel. Research and development should continue to make shale oil available when it is needed.

Introduction.

A high degree of co-operation between Government agencies and private industry has characterized experience in the United States during the past 5 years in studying oil-shale reserves, mining and crushing oil shale, producing shale oil, and manufacturing shale-oil products, to develop information needed to enable oil shale to supplement supplies of petroleum.

Pursuant to the Synthetic Liquid Fuels Act, approved April 5, 1944, the Bureau of Mines of the U.S. Department of the Interior has conducted an intensive research and demonstration-plant programme.[1] The Army, Navy, Geological Survey, and other Government agencies have co-operated fully, and specialists from private industry and educational institutions have devoted much time and energy to advance the studies. Co-operative efforts have been directed towards core drilling, crushing tests, research on retorting and refining, and pilot-plant processing of oil shale and shale oil. Meanwhile, several industrial concerns have conducted independent research and development.

Oil-shale Reserves.

Studies in recent years have shown that earlier estimates of the oil-shale reserves of the United States were very conservative. The nation's out-

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standing reserve is in the Green River formation, which was deposited during middle Eocene time in the beds of large lakes over an area of about 16,500 square miles in Colorado, Utah, and Wyoming.[2, 3] The richest deposits cover approximately 1000 square miles in the Piceance Creek Basin of northwestern Colorado. In that area, the main oil-shale measure is about 500 ft thick and has an average Fischer assay [4] of about 15 U.S. gal of oil a ton.[5] This is a deposit, in place, of more than 300,000 million brl of oil.

The lower part of the main oil-shale measure consists of a continuous series of beds, known as the Mahogany Ledge, which is 70 to 110 ft thick and has an average Fischer assay of about 30 gal a ton. Recent core drilling has indicated that this series in the 1000 square miles may yield 100,000 million brl of oil, allowing 25 per cent for mining losses. Although that estimate is for the best series of beds in the best-known and apparently the most-favourable area, it represents only a part of the oil that ultimately will be available from the Green River formation.

Oil-shale Mining.

It was evident from the beginning that production of shale oil will not be economic unless shale can be mined at very low cost. Large-volume operations and a high degree of mechanization are necessary.

The oil shale of the Green River formation is not a true shale, but a strong, tough marlstone that lies in massive horizontal beds. In the area west of Rifle, Colorado, the main oil-shale measure crops out in an almost vertical cliff at an elevation of 8000 to 8500 ft, about 3 miles north of the Colorado River and about 3000 ft above the river-bed (Fig. 1).

Barodynamic and demonstration tests of the roof stone over the Mahogany Ledge showed that rooms at least 60 ft wide can be run safely without timbering.[6, 7] Therefore, the bureau devised a mining method on the principles of underground quarrying. The Mahogany Ledge is mined in three benches, with a 60-ft roof span and pillars 60 ft square staggered in one direction, thus recovering three-quarters of the shale. Only the upper and middle benches are being developed in the bureau's demonstration mine.

The heading on the top level is drilled horizontally by four percussion drills mounted on a multiple-drill carriage operated by two men (Fig. 2). An 80-hole round 15 ft deep is drilled in one shift, and the holes are charged from an adjustable elevated platform mounted on a tractor. About 1500 tons is broken in one blast, and the shale is loaded by an electric shovel into 15-ton diesel trucks for transportation from the mine. The middle bench is drilled vertically with percussion drills mounted on another type of drill carriage. The roof and sides of pillars are scaled from a platform on a travelling crane (Fig. 3).

Analyses of production tests indicate that an output of 100 tons of shale per man-shift of underground labour and 50 tons per man-shift of total mine employees can be attained. In an operation on a scale of 150,000 tons a day, shale can be mined and conveyed to a retorting plant at a cost of about 57½ cents a ton. An additional 1½ cents a ton would provide a return of 4 per cent a year on the average unamortized part of the estimated initial capital investment of $34 million required to develop and equip the mines.

Research on Oil Shale and Shale Oil.

Laboratory and small pilot-plant studies of oil shale and shale oil in progress at the bureau's Petroleum and Oil-Shale Experiment Station in Laramie, Wyoming, are correlated intimately with the work at the Oil-Shale Demonstration Plant near Rifle, Colorado. In addition, close technical contact is maintained with private industry and with the bureau's research on petroleum. Studies have been made of the composition of oil shales, kerogen and shale oil,[8] and specific heats,[9] mineral constituents, and other properties of oil shale and spent shale have been determined (Figs. 4 and 5). Research has been conducted on rates at which kerogen is converted to oil under different conditions of extraction by thermal solution and conventional heating. Other studies have included rates of shale-oil cracking, hydrogenation of shale oil, and the characteristics of by-products from oil-shale operations.

A few of the conclusions drawn from this research are :—

(*a*) about 500,000 B.Th.U. is required to retort 1 ton of average Colorado oil shale;

(*b*) the olefins in shale-oil naphtha are predominantly of the straight-chain type;

(*c*) shale oil contains a high percentage of heterocyclic molecules;

(*d*) the tar acids in the shale oil contain phenol, cresols, and some xylenols and higher-molecular-weight homologues;

(*e*) the tar bases contain substituted pyridines and quinolines;

(*f*) most of the sulphur is in the form of substituted thiophenes; and

(*g*) good-quality crystalline and microcrystalline waxes can be extracted from Colorado shale oil.

The research has shown that kerogen contains enough hydrogen to produce a better product than the hydrogen-deficient oil usually obtained, if the reactions can be controlled properly.

Retorting Oil Shale.

N-T-U Retorts.

The two N-T-U retorts, each with a charging capacity of 40 tons, have been operated by the bureau since May 1947 under a wide variety of conditions to study the effects of variables such as air rate, recycle-gas rate, ratio of air to recycle gas, particle size, and grade of shale. During this operation about 8000 brl of oil was produced, and yields under the most favourable conditions have been from 85 to 90 per cent of the Fischer assay.[1, 10]

The N-T-U experimental programme was completed on March 1, 1949, and the retorts were placed in a standby condition. Any additional N-T-U operation will be for cost studies or to produce oil for refining or other uses.

Royster-process Retort.

Concurrently with the experimental N-T-U operation, the bureau conducted tests from January to September, 1948, on a smaller batch unit known as the Royster-process retort. In that process non-condensible gas

heated in pebble stoves is circulated through the shale bed. This work has provided data and experience for the design and operation of continuous retorts.[1, 10]

Gas-flow Retort.

The bureau's experimental retorting programme is now concentrated on a pilot plant for continuous operation, known as the gas-flow retort (Fig. 7). In this unit, which is similar to the Grand Paroisse, shale descending through the retort is preheated by flue gas and then raised to the retorting temperature by non-condensable gas from the retorting operation which flows horizontally through the shale. The cycle gas containing hydrocarbons from the shale passes to a condenser where the oil is removed. The part of the gas from the condenser that is to be recycled is brought to the retorting temperature by heat exchange with products from the combustion of fixed carbon in the spent shale.[1, 10]

Concurrently with tests of the gas-flow retort, the bureau is making engineering and cost studies of continuous retorts of other designs.

Union Oil Retort.

The Union Oil Co. of California has designed a retort which incorporates the internal-combustion and down-draft principle of the N-T-U retort but is continuous. A hydraulic piston at the bottom of the retort pushes the shale upward through the preheating, retorting, and combustion zones, and the spent shale is removed in the form of hot clinker by a scraper at the top of the retort. The air and gases drawn downward through the retort carry the oil vapours into the cool shale, where they are condensed.[11] The Bureau of Mines has supplied shale for the tests under a co-operative agreement with the company.

Fluidized Shale-retorting Process.

Pursuant to a co-operative agreement between the Standard Oil Development Co. and the Bureau of Mines, that company has reconstructed its fluid-catalyst-cracking pilot plant at Baton Rouge, Louisiana, to process oil shale, and tests are being made. One thousand tons of crushed shale was supplied by the bureau, with the aid of the Department of the Navy, and representatives of the bureau are observing the tests.

In this process crushed raw shale and hot spent shale from a burner vessel are carried by steam into a retorting vessel where the shale body is maintained in a " fluidized " state. Thus heat for retorting the raw shale is supplied by solid-to-solid contact with hot spent shale. The volatilized products from the retort pass overhead to a product-recovery and treating system. Spent shale containing fixed carbon is withdrawn continuously from the bottom of the retort and carried by a stream of air into the burner vessel, where it is maintained in a " fluidized " state and the fixed carbon is burned to supply the required heat.[12, 13, 14]

Thermofor Shale-retorting Process.

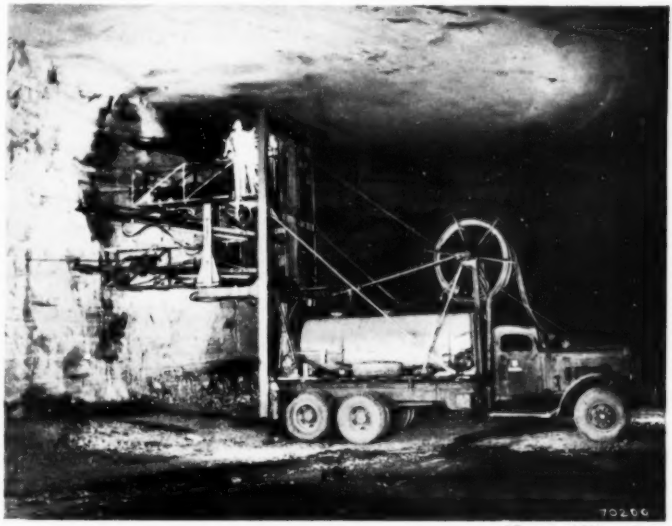
The Socony-Vacuum Oil Co. Inc. has developed a process for continuous retorting of a moving column of lump shale which flows by gravity through zones where the shale is successively preheated, retorted, burned free of

[*Bureau of Mines photo.*

FIG. 1.

AERIAL VIEW OF BUREAU OF MINES OIL-SHALE DEMONSTRATION PLANT NEAR RIFLE, COLORADO.

The plant is at right centre, the housing area in left foreground, and the mines are at the base of the steep cliff at upper left, 2200 ft higher than the plant.



[*Bureau of Mines photo.*

FIG. 2.

MULTIPLE-DRILL CARRIAGE IN OPERATION ON TOP LEVEL OF THE BUREAU OF MINES UNDERGROUND QUARRY.

[*To face p.* 844.

[*Bureau of Mines photo.*

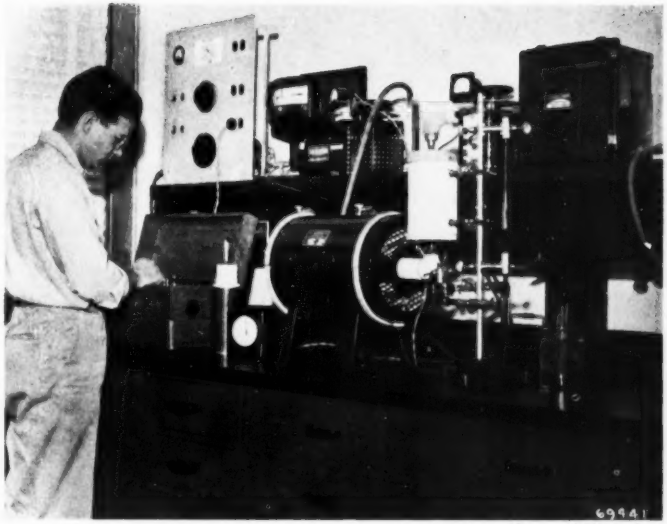
FIG. 3.

PORTABLE SCALING RIG USED IN REMOVING LOOSE ROCK FROM THE ROOF AND PILLARS OF THE QUARRY.

[*Bureau of Mines photo.*

FIG. 4.

PRECISION DISTILLATION COLUMNS AT BUREAU OF MINES EXPERIMENT STATION AT LARAMIE, WYOMING.



[*Bureau of Mines photo.*

FIG. 5.

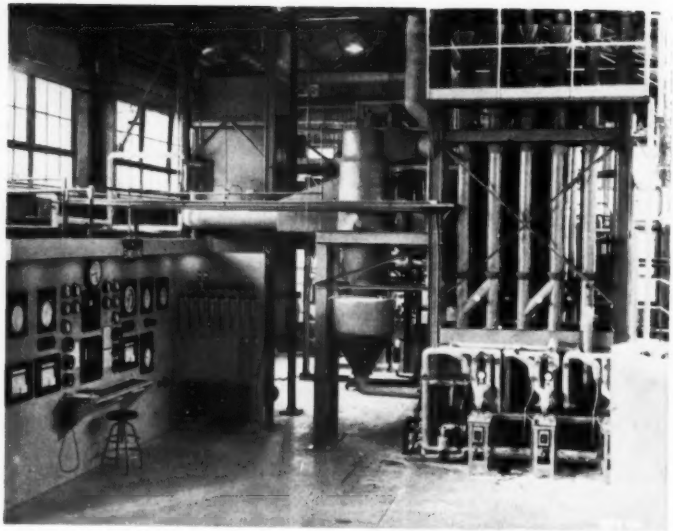
UNIT FOR PRE-HEATING OIL SHALES BY HOT GASES.

[*Bureau of Mines photo.*

FIG. 6.

BUREAU OF MINES OIL-SHALE DEMONSTRATION PLANT.

From right to left are crushing plant; shale storage bins; N-T-U retorts; refinery.

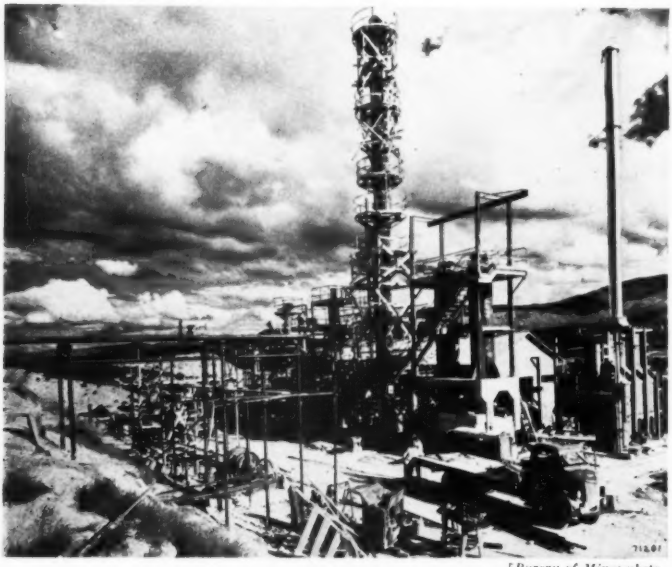


[Bureau of Mines photo.

FIG. 7.

GAS-FLOW CONTINUOUS RETORTING UNIT.

The retorting chamber is the high rectangular vessel to right of the instrument panel. Crushed shale comes through the roof of the building into a preheater and flows down through the retorting chamber. Hot gases passing horizontally through the moving shale bed carry oil vapours through the cyclone dust separator to the condensing system on the right.



[Bureau of Mines photo.

FIG. 8.

THE BUREAU OF MINES OIL-SHALE DEMONSTRATION PLANT DURING CONSTRUCTION.

carbon, and cooled. These effects are achieved by controlled use of air and gas recycling, and the zones are sealed with steam.[15, 16] This process has been tested in a pilot retort with a capacity of 1 ton a day, and development work is continuing.

Retorts for Commercial Operation.

Selection of retorts for commercial operation will require compromises between the advantages of: (*a*) mechanical simplicity, (*b*) high throughout, (*c*) large particle sizes of shale which reduce crushing cost, and (*d*) high recovery of available heat energy; and the disadvantages of: (*a*) dilution of oil vapours with products of combustion which reduce the recovery of the light ends of the oil, (*b*) expensive heat-exchanges and condensing equipment, (*c*) shale " fines " which are difficult to separate from the oil and may cause difficulty in disposal of spent shale, and (*d*) uses of steam or cooling water which require large water supplies. Economy in the use of water is imperative in western Colorado, where water is scarce and is allocated mainly to irrigation and municipal uses.

As the residence time required to bring the interior of a particle of shale to the temperature at which kerogen is converted to oil is a function of the particle size, no retort can be expected to process shale with a wide range of sizes. In crushing shale to any desired range, an appreciable volume of particles below the minimum will be produced. Therefore, it seems likely that an integrated commercial oil-shale operation will use more than one type of retort, or separate units of one type will be adapted to different sizes of shale, in order that shale of all particle sizes may be retorted.

Refining Shale Oil.

Shale oil differs from petroleum in that it contains a high proportion of olefinic hydrocarbons, and nitrogen and oxygen compounds that occur rarely in petroleum are present in relatively large amounts. Low-boiling distillates from shale oil have a hydrocarbon composition similar to cracked petroleum products, but include substances that are characteristic of tars from coal carbonization.

Studies by the bureau and private industry have shown that shale oil can be used as heavy fuel oil with relatively simple refining, but treatment before conventional refining will be required to convert it into satisfactory substitutes for other products now derived from petroleum. For the manufacture of high-quality gasoline, kerosine, and other products, some form of hydrogenation may be desirable to upgrade shale-oil distillates into the equivalent of good natural crude oil which can be processed by conventional means.

The bureau's demonstration plant at Rifle includes a small refinery with units for thermal cracking, low-temperature sulphuric acid treating, and sodium plumbite sweetening [1] (Fig. 8). Studies of hydrogenation are being pursued in collaboration with members of the bureau's staff who are working on hydrogenation of coal.

Economic Considerations.

At present the estimates of mining costs are on a reasonably firm basis. The cost of the shale in place, although small, is indeterminate, and costs of retorting and refining still involve many uncertainties. Therefore, the following should be considered tentative estimates only.

Bureau of Mines estimates indicate that $2·40 a barrel would cover the cost of mining, crushing, retorting, and all related utilities and facilities, exclusive of employee housing, to produce crude shale oil near Rifle from shale assaying 30 gal a ton with N-T-U retorts on a scale of 100,000 brl a day. This estimate includes depreciation at a rate of 6⅔ per cent a year, but does not include return on the investment.[1] Continuous retorts of types mentioned in this paper should produce oil at a considerably lower cost.

The Socony-Vacuum Oil Co. Inc., has estimated retorting costs with equipment of the Thermofor type at $1·10 a barrel when processing shale assaying 30 gal a ton. This estimate includes 20-year depreciation, 10 per cent profit on investments before taxes, and no credit for excess power. Allowance for costs of mining would raise the estimated cost of the crude shale oil to about $1·95 a barrel.

Murphree has estimated that 16·6 cents a gallon will cover the cost of the gasoline produced when shale oil is processed to yield a maximum of gasoline with an octane number considerably higher than that of the present premium grade. This estimate includes cost of housing for employees, 15 per cent for capital charges based on mining and manufacturing investments and transportation investment peculiar to the plant, and the cost of shale at $1·00 a ton.[17]

Schroeder has estimated that 5½ cents a gallon ($2·31 a barrel) of total products will cover the cost (including depreciation, but not including return on investment) of producing 850,000 brl a day of shale-oil products composed of 116,000 brl of gasoline and liquefied petroleum gases, 215,000 brl of middle distillate, and 519,000 brl of fuel oil.[18] This estimate assumes that shale assaying 30 gal a ton will be processed in continuous retorts.

It seems, therefore, that with demands for petroleum products increasing, costs of finding new oil rising, and technologic advances promising to reduce the cost of products from shale oil, research and development should be pressed forward, so shale oil can be made available whenever it is needed to promote the nation's welfare.

Acknowledgments.

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